THE AIRS TEAM SCIENCE DATA VALIDATION PLAN

M. T. Chahine
AIRS Team Leader

Edited by:
E. Fetzer

Contributions by:

M. Gunson, H. Aumann, L. Strow, D. Hagan, M. Hofstadter, E. Olsen, J. Susskind, P. Rosenkranz, H. Revercomb, L. McMillin, C. Gautier, D. Staelin, A. Huang, D. Tobin

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JPL
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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1. Introduction

This document describes the required validation activities for the AIRS/AMSU/HSB instrument suite in the post-launch period. The first sections summarize the required data sets and measurements which are expected to be readily available and highlights those which the AIRS Science Team deems as essential but have no current commitment for availability. They also describe the AIRS Science Team responsibilities and those of the Team Leader Science Computing Facility (TLSCF) at JPL. This plan is intended to guide the users of AIRS data and help coordinate non-Science Team members in their support of the validation activities. A summary timeline is presented, based on the expected EOS-Aqua instrument activation sequence and timing, data availability, and Science Team resources. Several later sections provide a technical description of how each AIRS / AMSU / HSB data product (from calibrated radiances to retrieved geophysical quantities) are validated, giving details of the required correlative measurements and data sets, the expected uncertainties in the retrieved quantities, and the time frame after launch when the validation activity is carried out.

1.1. Pre-Launch Activities

Several pre-launch activities directly support post-launch validation. These are detailed in the original AIRS Validation Plan and in the Algorithm Theoretical Basis Documents, all referred to above, but to recapitulate:

The first important activity is development of data storage, manipulation and display software. This has yielded a data warehousing system for several terabytes of online and offline storage. This system will hold a significant fraction of the data collected for AIRS validation. Additional effort has been devoted to developing software for display of these data.

The second major pre-launch activity supporting AIRS validation is the creation of a simulated dataset AIRS Level 1B, Level 2 and associated truth files. This has been an ongoing activity of the AIRS Science Team. This data set was created for the CAMEX-3 calibration / validation flight that occurred on September 13, 1998. Correlative measurements included in this simulation are NAST-I radiances and operational radiosondes.

1.2. Laboratory Spectroscopy

,Accurate spectroscopic parameters are fundamental to the elimination of biases and minimization of uncertainties in retrieved geophysical parameters from the AIRS / AMSU / HSB multispectral instrument suite. Several new laboratory measurements of the spectroscopic parameters of key trace gases (e.g., water vapor) have been included in the forward models used to invert AIRS spectral data. Continued efforts in this area are desired, to characterize the line shapes, pressure-broadening, pressure-induced shifts, and temperature dependence of these spectroscopic parameters for critical gases such as CO_2, H_2O, and O_3. (See Section 5.1.4).

1.3. Document Overview

This plan consists of several Sections:

1. Section 2: Executive Summary. This section contains a list of the data sets needed for AIRS validation, their current status, a proposed schedule for the first year of activities, and AIRS Science Team member responsibilities.
2. Section 3: AIRS Validation Approach. This section describes the approach the AIRS Science Team will use to validate the AIRS observations.
3. Section 4: Validation Sequence. This section describes the order of events needed for validation of the AIRS instrument and products.
4. Section 5. Prioritized Validation Requirements. The intended audience is scientists planning or executing validation field campaigns. This section describes high-priority observations uniquely necessary for the validation of AIRS products.
5. Section 6. Aqua Spacecraft Coordinated Validation Activities. The AIRS / AMSU / HSB instrument suite shares some measurements with all other instruments on the EOS-Aqua platform. This section describes those measurements, the conditions under which they are best validated, and the nature of the correlative observations needed for their validation.
6. Sections 7 through 17: Validation of specific quantities. These sections describe the validation methodologies for specific observed quantities. Included are expected schedules and workforce requirements. Also described are requirements shared with other EOS-Aqua instruments.

1.4. Supporting Documents

The following documents provide important supporting material to this Plan. The original AIRS Validation Plan is:

AIRS Team Science Data Validation Plan, Core Products, JPL D-16822, Version 1.2, August 15, 1997

An overview of the AIRS instrument, and measurement requirements are given in:

AIRS Science and Measurement Requirements Document, JPL D-6665 Rev 1 September 1991 AIRS Brochure

The AIRS calibration activities are detailed in:

AIRS Instrument Calibration Plan, JPL D-16821, Preliminary, October 14, 1997

The Algorithm Theoretical Basis Documents describe detailed operations of the processing algorithms. They are:

AIRS Algorithm Theoretical Basis Document, Level 1B, Part 1: Infrared Spectrometer, JPL D-17003, Version 2.0, January 4, 1999

AIRS Algorithm Theoretical Basis Document, Level 1B, Part 2: Visible/Near-Infrared Channels JPL D-17004, Version 2, January 4, 1999

AIRS Project Algorithm Theoretical Basis Document, Level 1b, Part 2: Microwave Instruments , JPL D-17005, Version 1.2, November 15, 1996

AIRS Algorithm Theoretical Basis Document, AIRS-Team Unified Retrieval For Core Products, Level 2, JPL D-17006, Version 1.7, September 18, 1997

2. Executive Summary

This section outlines the required validation activities for the AIRS / AMSU / HSB instrument suite in the post-launch period.

2.1. Sequence of Activities

A series of increasing complex data sets is needed to validate AIRS performance. These are listed below. (Note that Phase A during the first two weeks of operations does not depend upon external validation information).

Phase A: ***Instrument Checkout***

Time: AIRS startup + 2 weeks

Geophysical State: Clear coastline crossings

Vicarious Data Sets Needed: None.

Process Addressed: Instrument behavior

Activities: Confirmation of AIRS online blackbody behavior. Confirmation of AIRS / AMSU / HSB instrument boresight coalignment at coastal crossings.

Validation Goals: Level 1A processing.

Phase B: ***Simple Field Validation***

Time: AIRS startup + 2-15 weeks

Geophysical State: Clear sky over calm ocean.

Vicarious Data Sets Needed: Sea Surface Temperatures (SSTs). Radiosonde observations of temperature and water vapor profile. MODIS or AIRS VIS / NIR cloud mask, or, confirmation of clear sky conditions over an AMSU footprint.

Processes Addressed: Water vapor contribution in window region.; microwave-only retrieval; infrared retrieval with simple surface and no clouds.

Activities: Regress AIRS window region brightness temperatures against SSTs and humidity. Compare microwave-only retrievals of temperature and moisture with observations. Compare IR retrievals of temperature and moisture with observations.

Validation Goals: Level 1B processing. Microwave-only retrieval. IR retrieval under simplest geophysical conditions.

Phase C: ***Cloud Property Validation***

Time: AIRS startup + 12-16 weeks

Geophysical State: Cloudy sky over calm ocean.

Vicarious Data Sets Needed: SSTs; AIRS VIS / NIR cloud mask or MODIS cloud mask. Radiosonde observations of temperature and water vapor profile.

Processes Addressed: Cloud clearing; cloud fraction retrieval.

Activities: Compare retrieved cloud fraction with cloud mask. Compare cloud-cleared radiance in known cloud-free AIRS footprints. Compare IR retrievals with profiles of temperature and water vapor.

Validation Goals: Cloud clearing algorithm. Infrared retrieval with clouds and simple surface.

Comments: This activity depends upon well-validated microwave retrieval.

Phase D: ***General Retrieved Parameter Validation***

Time: AIRS startup + 20 weeks

Geophysical State: Cloudy sky over land.

Vicarious Data Sets Needed: Surface temperatures and emissivities over one or several AMSU footprint (ARM CART site); AIRS VIS / NIR cloud mask or MODIS cloud mask. Observations of temperature and water vapor profile. Any additional cloud information.

Processes Addressed: General condition of surface properties and cloudiness.

Activities: Retrieval validation under wide range of conditions.

Validation Goals: Level 2 retrieval process.

Comments: This activity will confirm AIRS retrieval.

Phase E: ***Extended Validation Activities***

Time: AIRS startup + 36

Geophysical State: General.

Vicarious Data Sets Needed: Large sets of surface, profile, and cloud states; ozone soundings; observations from other Aqua instruments of surface temperature, cloud properties and water vapor loading.

Processes Addressed: General conditions of surface properties and cloudiness; long term instrument monitoring.

Activities: Statistically significant retrieval validation.

Validation Goals: Level 2 products.

Comments: This activity will provide the final estimates of AIRS standard product uncertainties, and begin to validate some of the AIRS research products.

2.2. Highest Priority Data Sets

The table below lists the validation data sets required for AIRS / AMSU / HSB product validation. The data sets and activities above the bold line are high priority for first year of AIRS operation.

Product Validated and Validation Priority

Data Set Type	Level 1B Microwave	Level 1B Infrared	Forward Model	IR Cloud Clearing	Sea Surface Temperature	Land Surface Temperature	Temperature Profiles	Lower Tropospheric Water Vapor	Upper Tropospheric Water Vapor[1]	Ozone[1]	Cloud Properties	VIS / NIR Radiances	Microwave Precipitation Estimates[2]
*Comprehensive set of ocean observations, cloud free conditions		•	•		•		•	•					
*Comprehensive set of ocean observation, cloudy conditions.				•	•		•	•			•		
*Comprehensive set of land observations, general conditions				•		•	•	•			•	•	
AIRS-dedicated radiosondes							•	•					
Radiance observations from aircraft	•	•									•		
Upper tropospheric humidity measurements[1]			•						•				
SST from buoys, with cloud mask				•	•								
Operational land surface temperature observations						•							
Operational radiosondes							•	•					
Coordinated ozonesondes										•			
NEXRAD over Continental United States													•

Table 1. AIRS validation data sets versus validated products.

*'Comprehensive set' contains simultaneous observations of spectrally resolved upwelling surface radiance, surface temperature, and tropospheric profiles of temperature and water vapor, and clouds if implied; all at time of Aqua overpass for 50 or more overpasses, with roughly equal representation of day and night.

[1]Upper tropospheric humidity has high science priority, but difficult to validate early in instrument operations.

[2]Precipitation prevents retrieval of all other Level 2 quantities, so requires a unique data set.

2.3. Data Set Support Status

The table below show the status of support for validation data sets to be used by the AIRS Science Team in the first year after beginning of AIRS / AMSU / HSB instrument operations.

Data Type	Status of activities: Planned / Committed?	Data sources
*Comprehensive set of ocean observations, cloud free conditions	YES / NO	Aqua validation sites (MODIS cruise, buoys).
*Comprehensive set of ocean observation, cloudy conditions.	YES / NO	Aqua validation sites
*Comprehensive set of land cloudy conditions	YES / YES	U. Wisconsin ARM CART activities
AIRS-dedicated radiosondes	YES / NO	AIRS validation activities.
Radiance observations from aircraft	NO / NO	Aqua validation underflights
Dedicate upper tropospheric humidity observations	YES / NO	Aqua validation underflights
SST from buoys, with cloud mask	YES / NO	Aqua validation sites / operational buoys.
Land surface temperature observations	YES / NO	Operational data
Operational radiosondes	YES / YES	Operational data
Coordinated ozonesondes	YES / NO	Ozone monitoring network
NEXRAD over Continental United States	YES / YES	Commercially available product

Table 2. Status of all validation data sets.

*'Comprehensive set' contains simultaneous observations of spectrally resolved upwelling surface radiance, surface temperature, and tropospheric profiles of temperature and water vapor, and clouds if implied; all at time of Aqua overpass for 50 or more overpasses, with roughly equal representation of day and night.

Table 3. Status of AIRS Science Team surface validation activities and associated data sets.

Ranking: **1** – Vital; **2** – Enhancement (significant increases the yields of in-situ for statistical meaningful validation); **3** – Optional
Priority: **1** – Highest Priority; **2** – High Priority; **3** – Moderate Priority

* Requires EOS Validation funding
SHIS- Scanning HIS; PAERI-Polar AERI; SAERI-Surface AERI; MAERI-Marine AERI
UTH-Upper Tropospheric Humidity, TPW – total precipitable water vapor

AIRS Surface Data Validation Activities (Page 1 of 2)

AIRS Product to be Validated	Validation Data	Ranking	Accuracy	Sites/Campaigns-Priority
Water Vapor				
	Sondes	1	~5-50 %	ARM (routine operations) – 1 Special ARM (overpass coordinated) – 1 * International – 2 * SSEC (Madison, WI) – 2 * GPS (monumented sites)– 3
	GPS TPW	1	~5-10 %	
	Microwave Radiometer (MWR) TPW	1	~3-5 %	
	AERI	1	~10 %	
	Tower/Surface	2	~2-10 %	
	Raman Lidar / Dial UTH	1	~10 %	
	SHIS/NAST-I	1	~10 %	Field Campaigns – 1 *
	AERI	1	~10 %	
	LASE	1	~5 –7 %	
	Sondes	1	~5-50 %	
Temperature				
	Sondes	1	~0.5 K	ARM (routine operations) – 1 Special ARM (overpass coordinated) – 1 * International – 2 * SSEC (Madison, WI) – 2 * GPS (monumented sites)– 3
	AERI	1	~0.8-1.0 K	
	ACARS	2	~0.5 K	
	Tower/Surface	2	~0.2-0.5 K	
	SHIS/NAST-I/-M	1	~0.8-1.0 K	Field Campaigns – 1 *
	AERI	1	~0.8-1.0 K	
	Sondes	1	~0.5 K	

AIRS Surface Data Validation Activities – (Page 2 of 2)				
AIRS Product to be Validated				
SST	**Validation Data**	**Ranking**	**Accuracy**	**Sites/Campaigns – Priority**
	Buoys	1	~0.2 K	Field Campaigns – 1 *
	MAERI	1	<0.1 K	
	SHIS/NAST-I/-M, SSTR	1	~0.2 K	
	Sondes T/Q	1	~0.5K/ 5-50 %	
	GPS-TPW	2	~5-10 %	
	MWR-TPW	1	~3-5 %	
LST				
	SAERI	1	~0.2 K	Field Campaigns – 1 *
	SHIS/NAST-I/-M	2	~0.4 K	
	MODIS	3	~0.5 K	
	Sondes T/Q	1	~0.5K/ 5-50 %	
	GPS-TPW	2	~5-10 %	
	MWR-TPW	1	~3-5 %	
Radiance				
Direct Validation	SHIS/NAST-I/-M	1	~0.2-0.4 K	Field Campaigns – 1 *
	PAERI/MAERI/ SAERI	2	~0.2 K	
	MODIS/GOES	3	~0.5 K	
Indirect Validation	Fast Model	1	~0.1 K	ARM (routine operations) – 1 Special ARM (overpass coordinated) – 1 * International – 2 * SSEC (Madison, WI) – 2 * GPS (monumented sites)– 3
	Raman Lidar/Dial UTH	1	~10 %	
	Ozone Sondes	1	~0.5K/5-50 %	
	Validation T/Q Profile	1	~0.5K/5-50 %	
	PAERI/MAERI/ SAERI	1	~0.2 K	

2.4. AIRS / AMSU / HSB Validation Timeline

	AIRS First Year Validation Activities	
	Time from Aqua Launch (Months)	**Products Validated**
Clear / Cloudy Sky Identification	3	
Oceanic Sites (not polar)		
Microwave Spectra	3	L1B MW
IR window channels, cloud-free	4	L1B IR
Full IR spectra, cloud-free	5	L1B IR
T, H2O, O3 profiles, cloud free	7	Level 2 core, cloud free
Full IR spectra, cloud-cleared	7	Level 1b cloud cleared
T, H20, O3 profiles + cloud properties	8	Level 2 core (cloudy ocean)
Land Sites (not polar)		
Full IR spectra, clear land	6	L1B IR
T, H2O, O3 profiles , cloud free	8	Level 2 core (clear land)
T, H20, O3 profiles + cloud properties	9	Level 2 core (cloudy land)
Ice Sites		
Full IR spectra, clear ice	10	L1BIR
T, H2O, O3 profiles , cloud free	11	Level 2 core (clear ice)
T, H20, O3 profiles + cloud properties	12	Level 2 core (cloudy ice)

Table 4. Time line for completing global validation of core level 2 products within 12 months of launch.

2.5. AIRS Science Team Member Validation Analysis Responsibilities

Data Product

Responsibility	Level 1B Microwave (AMSU)	Level 1B Microwave (HSB)	Level 1B Infrared (spectral) clear	Level 1B Infrared(radiometric) clear	Level 1B IR Cloud Cleared	Sea Surface Temperature	Land Surface Temperature and Emiss.	Temperature Profiles	Water Vapor Profiles	Ozone	Cloud Properties (IR)	Cloud Properties (VIS)	VIS / NIR Radiances	Microwave Precipitation
Rosenkranz	•													
Staelin		•												•
Strow			•											
Susskind					•									
Chahine											•			
Revercomb							•							
McMillin								•	•					
Gautier												•	•	
Aumann				•										
TLSCF/JPL						•				•				

Table 5. AIRS Science Team member validation responsibilities.

H. H. Aumann (JPL): AIRS instrument verification of on-board calibration and Level 1b radiometric validity during Phase A Instrument Checkout. Sea surface properties including temperature during Phase B Spot check Field Radiance Validation.

M. T. Chahine (JPL): Infrared Cloud Properties

C. Gautier (UCSB): Verification of VIS / NIR measurements in Phase A Instrument Checkout. Validation of clear sky conditions from VIS / NIR measurements in Phase B. Validation of cloud properties starting in Phase C. Coordination with MODIS Land Validation activities and comparison of MODIS/AIRS surface quantities.

M. Goldberg (NOAA): Global validation of level 1b (using EF decomposition). Validation of the first product and emphasis on uncertainties assigned to temperature and humidity in Phase D. Cross-validation with NOAA-15 and –16 retrieved quantities.

L. McMillin (NOAA): validation of temperature and moisture profile using global statistics starting in Phase C.

H. Revercomb (U. Wisconsin), **Smith** (Langley): coordinating ARM-CART site observations and synthesis of atmospheric state from these measurements for intensive spotcheck validation of AIRS products in Phase D. Land surface temperature and emissivity validation. Cross-validation with MODIS products.

P. W. Rosenkranz (MIT): AMSU verification during Phase A. Microwave-only retrievals of temperature and humidity during Phase B.

D. Staelin (LL/MIT): HSB verification during Phase A. Validation of precipitation quantities in Phase C. Cross-validation of precipitation quantities with NEXRAD data.

L. L. Strow (UMBC): Forward model validation starting with clear sky radiance measurements in Phase B.

J. Susskind (GSFC): validation of "clear flag" in phase A. Validation of the cloud-clearing algorithm and cloud-cleared radiance product during phase B. Validation of derived IR cloud properties in Phase C. Validation of Final Product quantities in Phase D.

2.6. AIRS TLSCF Responsibilities

The AIRS Team Leader Science Computing Facility (TLSCF) has primary responsibility for supporting the validation activities of the AIRS Science Team. TLSCF responsibilities are to:

- Provide data processing software and ancillary file updates to ESDIS.
- Support AIRS Science Team Validation activities.
- Archive AIRS validation data sets.
- Validate core products as directed by the Team Leader and Science Team members.
- Reprocess AIRS data with updated software.

3. AIRS Validation Approach

AIRS validation activities are intertwined with the other instrument activities of spectral calibration and parameter retrieval. These activities are described in the AIRS Algorithm Theoretical Basis Documents and in the AIRS Calibration Plan, listed above. Calibrated radiances and retrieved quantities from the AIRS system are the result of a complex flow of data through instruments and software. Potential sources of uncertainty occur at many points in this flow, and all can corrupt the quantities ascribed geophysical significance. Additional uncertainties can come from incomplete knowledge of the spectral information used in the AIRS forward radiance model.

Exploiting Observed Biases and Variances. The first goal of AIRS validation activities is to use geophysical observations from many sources to elucidate the uncertaintities introduced by the AIRS / AMSU / HSB instruments and the associated processing system. These vicarious observations are sometimes referred to as 'truth' when in fact they have their own internal uncertainties that must be considered in the analysis. Nevertheless, the error characteristics of the vicarious observations may be presumed reasonably well know in advance. These place lower bounds on the biases and variances of any residuals between vicarious observations and AIRS observations. AIRS validation activities will first attempt to identify those areas and conditions under which biases and variances are 'unreasonable,' based upon the known noise properties of the vicarious observations.

Once conditions of unexpectedly large uncertainty are encountered, the second goal of the AIRS validation activity is to identify the presumed sources of this uncertainty. These sources can be of several types: poor instrument calibration, spectroscopic uncertainty in the forward model, incorrectly parameterized physics in the cloud clearing, and incorrect convergence within the retrieval algorithm are just a few potential error sources that can be studied through the validation process. We expect that identifying and correcting these error sources will be the major activity of the AIRS Science Team in the first year or so of AIRS operations.

Only after instrument and software errors have been corrected will the third stage of validation begin. This stage involves defining the magnitude and conditions of occurrence of the uncertainties associate with the AIRS instrument. These numbers define the operating conditions of the instrument. The system can be considered fully validated when they are obtained through comparison of the AIRS parameters with the correlative observations.

Importance of Sequencing. The AIRS / AMSU / HSB instrument suite will observe a wide range of cloudiness, temperature, humidity and surface conditions. Many of these will be difficult to validate, particularly in the first six months of operation when instrument and software conditions are still being explored. Section 4 below describes the hierarchy of observations needed for AIRS validation, particularly in the first year of operation. Briefly, conditions need to be observed in the following order: cloud-free oceans, cloudy oceans, cloud-free land and cloudy land. All these conditions require observation sets complete enough to ascertain AIRS uncertainties with statistical significance.

Infrastructure Requirements

The initial goal of the AIRS validation activity is an understanding of unanticipated situations with the instrument and processing software. This requires interactions between all people working with instruments and the data. The infrastructure to support this interaction must be in place prior to launch of the AIRS instrument. Current networking capabilities prevent practical transfer of AIRS calibration data between JPL and Science Team members in the eastern U. S. This, and many other infrastructure problems must be resolved before launch.

4. Validation Sequence

This section supplements the validation sequence put forth in the Executive Summary section above. It further describes the sequence of data sets to be used for AIRS validation.

The validation of the AIRS retrieval software, and the associated geophysical quantities, will precede under the following sets of conditions:

4.1. Clear Sky Sea Surface Observation

Clear oceans will provide the simplest set of validation conditions because oceanic surface properties are roughly constant over an AMSU footprint and the field of view is not obscured by clouds.

Sea surface temperature under clear sky conditions is of interest to all Aqua instruments. MODIS, for example, is dedicating considerable effort to characterizing sea surface conditions (see http://modarch.gsfc.nasa.gov/MODIS/OCEANS/#SST). AIRS will utilize these and other such Aqua observations because they represent the simplest geophysical conditions of clear sky and fairly homogeneous temperature and emissivity over the scale of a single AMSU footprint (~45 km). Complete suites of other vicarious observations will be needed in addition to SST: these include profiles of temperature, water vapor mixing ratio, and ozone. Oceanic radiances from several sources will be available from several sources, including M-AERI instruments on ships and buoys, and NAST-I on aircraft. These observation sets will be used to validate radiances, the AIRS forward model, and the AIRS retrieved quantities

The importance of clear sky ocean observations places a premium on well-instrumented ocean sites, and confirmation that a view is indeed cloud-free in the infrared.

4.2. Cloudy Sky Sea Surface Conditions

Once the AIRS instrument functionality is confirmed over clear ocean, the next step will be comparison of cloud parameters over ocean. This activity will require demarcation of cloudy and clear scenes.

While the cloudy ocean conditions are distinct from –and their interpretation more difficult than—the clear sky conditions, any opportunity to obtain cloudy sky ocean observation should be exploited.

4.3. Clear Sky Land Surface Conditions

Because of land inhomogeneity issues, the validation of the retrieval process over land will follow that over ocean. A similar suite of observations as described above for clear ocean conditions will be needed for clear land, however.

The ARM CART sites and other well-instrumented land stations will provide a very complete observation set over a wide range of conditions.

4.4. Cloudy Sky Land Surface Conditions

The final set of observations needed is as complete as possible a characterization of the atmosphere under general conditions of cloudiness and land surface emissivities. This data set will available through the ARM CART site approximately nine months after Aqua launch. This dataset is listed in the section below under 'Comprehensive Observations.'

5. Prioritized Validation Requirements

This section provides a synopsis of the more comprehensive methodologies detailed in later sections. The purpose of this section is to clarify the planning and coordination of AIRS validation activities with other EOS instrument teams. The measurements described here are deemed vital to the AIRS validation activity. Particular emphasis is given to those activities requiring coordinated, multi-instrument observations that are not part of standard EOS validation activities.

5.1. High Priority, AIRS-Unique Observation

These observations are of two types.

The first group of observations requires vicarious observations of ocean under clear sky conditions. The vicarious observations will consist of sea surface temperature, temperature profiles, humidity and ozone, and associated upwelling radiances in the infrared and microwave.

The second group is a comprehensive set of correlative observations of the quantities measured by AIRS. Most of these observation should be available from ground-based instruments at well-instrumented locations like the DOE ARM-CART sites. The fundamental observational set will require observations for approximately one season six months after launch of the EOS-PM1 platform. In addition to ground-based observations, coordinated overflights with well-instrumented aircraft will be useful in characterizing the upwelling radiance in both the infrared and the microwave. Follow-on data sets to the initial six-month observational set will be needed during four one-month periods per year during operation of the AIRS instrument suite.

The third group of high priority validation observations concerns upper tropospheric water vapor. The upper tropospheric water vapor validation measurements will be needed roughly one year after the startup of the AIRS instrument suite. Water vapor is of great scientific interest and AIRS will provide a high-quality global climatology. Nevertheless, the formal validation of upper tropospheric water vapor will be a difficult task. A campaign dedicated to its validation is considered high priority by the AIRS Science Team. Such a campaign will require coordinated deployment of the ER-2, DC-8 and associated sondes. A set of observations similar to those from the CAMEX-3 Calibration / Validation flight will provide this valuable information. This flight will be needed roughly one year or later after the beginning of the AIRS mission.

5.1.1. Atmospheric Conditions over Clear Oceans

The simplest AIRS retrievals occur over clear oceans. Associated correlative measurements have these requirements:

- Unambiguous identification of cloud-free regions.
- A complete suite of sea surface temperature, temperature profiles, water vapor profiles, ozone profiles, and several baseline sets of spectral observations.

- Preferred locations are the MODIS checkout cruise, and the CERES instrument platform.
- Measurements to begin no earlier than 3 months from start of AIRS operations, or roughly 5 months from launch of Aqua spacecraft.
- Measurements must be made in coordination with other EOS-Aqua instruments to enable cross-validation of similarly retrieved quantities.
- A complementary set of cloudy observations is implicit in these data, given the frequency of cloud occurrence. These cloudy ocean observations can be utilized in later validation activities.

5.1.2. Comprehensive Observations

Once a complete suite of clear-sky oceanic observations are obtained, the following observations are the highest priority of the AIRS Science Team. They are characterized by:

- A complete suite of correlative observations including surface properties, temperature profiles, water vapor profiles, ozone profiles, cloud properties, and several baseline sets of spectral observations. Upwelling infrared and microwave radiances observed from ER-2 are a desirable component of this set, but are considered lower priority than a complete set of other observations.
- Preferred locations are the DOE ARM/CART sites: 1) SGP, 2) TWP, 3) North Slope.
- Most important is a one- to three-month observational set beginning 6 to 9 months after startup of the AIRS instrument suite.
- Additional one-month observational sets every season during AIRS operation.
- This correlative observation set will be most useful if taken at times of AIRS overpasses of 1:30 AM and 1:30 PM.

5.1.3. Upper Tropospheric Humidity

- Complete suite of aircraft observations of upper tropospheric water vapor.
- Over subtropical ocean region.
- Several hours and / or several hundred kilometer flight path to include clear and cloudy conditions.
- No earlier than one year after AIRS instrument suite is operating.

5.1.4. Laboratory Spectroscopy

AIRS science and validation activities will benefit from the following spectroscopic information:

- The water continuum, both in the window region and in the 12-1400 cm^{-1} region.
- The shape of the strong water vapor lines over a range of temperature, especially in regions from about 1 to 10 cm^{-1} from line centers.

6. Aqua Spacecraft Coordinated Validation Activities

AIRS shares some observations with other instruments on the EOS Aqua platform. Scientific interest and resource constraints suggest coordinated efforts to validate these quantities across the EOS Aqua instrument suite. These cross-instrument validation activities are described in more detail with the individual products below. This section lists exhaustively the validation activities AIRS expects to share with other EOS Aqua instruments.

AIRS / AMSU / HSB Observed Radiance	Aqua Instruments Making Similar Observations
Infrared radiances	*CERES, MODIS*
Near infrared radiances	*MODIS*
Microwave radiances	*AMSR*

Table 6. Radiance observations shared with other EOS Aqua instruments.

AIRS / AMSU / HSB Observed Quantities	Aqua Instruments Utilizing Similar Observations
Sea surface properties	*AMSR, CERES, MODIS*
Land surface properties	*AMSR, CERES, MODIS*
Temperature profiles	*CERES, MODIS*
Water vapor distribution	*CERES*
Total water vapor	*CERES, MODIS*
Infrared cloud fraction	*MODIS, CERES*

Table 7. Geophysical observations shared with other Aqua instruments.

These validation activities will be coordinated with the EOS-Aqua Validation Group.

7. Microwave Radiance Validation

7.1. Introduction

Although microwave radiance is not one of the core science products of the AIRS / AMSU / HSB instrument suite, its proper validation is essential to the ensuing step of retrieving geophysical quantities from the radiances.

7.2. Primary Microwave Radiance Validation Methodologies

Microwave brightness temperatures will be compared with brightness temperatures directly observed from other satellites or aircraft. The currently operational NOAA-15 carries AMSU-A and AMSU-B instruments, and launch of NOAA-16 is expected prior to EOS-Aqua.. Although the NOAA-15 AMSU-B suffers interference from spacecraft transmitters, subsequent AMSU-B instruments and also HSB will have improved interference shielding.

Airborne instruments also measure upwelling microwave radiation in the same spectral bands as HSB and AMSU. AMSU channels 3 through 8 are duplicated on the NAST-M, which can fly on the ER-2 or the Proteus aircraft. All four HSB channels are duplicated by the MIR, an ER-2 instrument. Both of these instruments have wide observation swaths, so their data can be averaged to simulate an AMSU or HSB footprint; horizontal structure within the footprints can also be examined.

7.3. Secondary Microwave Radiance Validation Activities

Microwave brightness temperatures will be compared with calculations based on co-incident temperature and moisture profiles from dedicated radiosondes, using the forward radiative transfer model described in the ATBD. Clear sky would be preferred for such comparisons due to the difficulty of determining absorption by cloud liquid water.

7.4. Microwave Radiance Data Sources

AMSU-A, AMSU-B, NAST-M, MIR

8. AIRS Validation: Level 1B Spectral Radiances

8.1. AIRS Radiance Validation Requirements

Spectral Resolution	1% of SRF width knowledge of the SRF centroids; SRF width validated to 1%
Radiometric Response	3% absolute of full dynamic range

Table 8. AIRS infrared radiance validation requirements.

8.2. Background

This section addresses the validation of the AIRS Level 1b calibrated radiances. The radiometric and spectral calibration of AIRS is discussed in some detail in the AIRS Instrument Calibration Plan and in the AIRS Level 1b ATBD. The term spectral calibration refers to our knowledge of the AIRS spectral response functions (SRFs), which includes their shape, spectral location (centroids), and how these quantities change with temperature and AIRS focus.

Validation of AIRS Level 1B radiances is divided into two separate but related aspects: validation of the radiometric accuracy and validation of the SRFs. AIRS Level 2 retrievals use a fast radiative transfer model (AIRS-RTA) to minimize the difference between observed and computed radiances. Since the forward model is very sensitive to the exact form of the AIRS SRFs, we consider the validation of the SRFs part of Level 1B validation. Although extensive ground calibration of AIRS has given us much information on the form of the SRFs, they are not known exactly until AIRS is in-orbit for reasons described later. (See the AIRS Level 1 ATBD for details of on-orbit spectral calibration).

8.3. Validation of AIRS Absolute Radiances

Validation of the AIRS radiometric accuracy also touches in the validation of sea-surface temperature products. AIRS sea-surface observations provide the best opportunity for validation of the components of the AIRS absolute radiometric calibration that are common to all detectors, such as the temperature/emissivity of the on-board blackbody calibrator (OBC) and scan mirror angle effects. The spectral validation activities discussed later in this section will depend in part on validation of the absolute radiance calibration (at least for high radiance scenes) through observations of well characterized scenes such as the sea-surface.

While the spectral radiance validation focuses on wavelengths of high spectral contrast, the absolute radiance validation will be carried out in spectral regions relatively free of spectral features. A number of regions of high atmospheric transmission have been selected for this validation effort. The intervals are roughly 10 and 20 cm^{-1} wide, and are found on several AIRS detector arrays, including M1a, M3, M4d, M5, M6, M7, M8, and M9. The central wavenumbers of the selected regions are roughly 2620, 2670, 1400, 1260, 1100, 980, 940, 870, 830 and 780 cm^{-1}. These regions are selected based on the AIRS detector sensitivity and the atmospheric transmission within the bandpass. However, these regions are not without some spectral absorption, e.g., nitric acid absorption near 870 cm^{-1}, continuum absorption at most of these wavelengths. As part of the pre-launch activities, we will carry out simulations to optimize the specific pass bands used for this analysis and to precalculate the transmission for representative climatological conditions.

The first concern in this effort will be to ascertain the stability of the measured responses from day to night where small diurnal variations are expected, to look for fluctuations in observations between detector arrays, and to determine if the magnitude of the observed radiances are near expected values. We will then correct the radiances for atmospheric attenuation, and compare the derived upwelling radiance at the surface with the available SST measurements. Previous work has shown that we will be able to retrieve SST to within an accuracy of 1K using a physical retrieval technique (Nalli and Smith, 1998; Hagan and Nalli, 1999), but one that does strongly depend on the quality of the first guess atmospheric profile. This retrieval technique is essentially a more complete version of the split window correction technique. As confidence is gained in the performance of the AIRS instrument over the eastern tropical Pacific region, this methodology will be expanded to other ocean areas of different surface temperature.

8.4. AIRS Spectral Response Functions (SRFs)

The validation of the AIRS spectral calibration will rely on comparisons between observed and computed radiances, so it will also involve simultaneous validation of the forward model spectroscopy and the fast radiative transfer parameterization. Separately validating the various aspects of the Level 1B radiances (*i.e.,* radiometric calibration, SRF knowledge, spectroscopy, fast model parameterization) will require a wide range of inter-comparisons under many atmospheric conditions. Although it may appear difficult to separate out these various effects, the copious redundancy (in terms of weighting functions) in the AIRS spectral channels, coupled with good models for instrument errors and spectroscopic errors, will allow us to de-couple these effects and in large part validate them separately.

Conceptually, AIRS convolves the Earth's up-welling monochromatic radiances with the AIRS SRFs. The earth view detector counts are converted into radiances in the standard way using detector space view counts and on-board blackbody calibrator (OBC) view counts recorded in-between each scan line. These measurements, combined with the OBC temperature, provide the basic radiometric calibration of AIRS. Early ground calibration results generally suggest that the OBC illumination of the detector focal plane is quite uniform, that the detector responses are very nearly linear, and that scan angle effects are relatively small. Consequently, we hope that absolute radiometric calibration and validation will primarily be involved with characterizing the OBC temperature and stability, which are essentially independent of spectral channel.

The overall goal is to validate and possibly improve our *models* of the AIRS instrument behavior, the AIRS-RTA, and the spectroscopy in the AIRS-RTA and in doing so validate the AIRS Level 1B radiances. Since these models are largely independent of scan angle and cloud amount, this process will concentrate on nadir views of fields deemed very clear. Figure 1 illustrates the basic flow of information in the Level

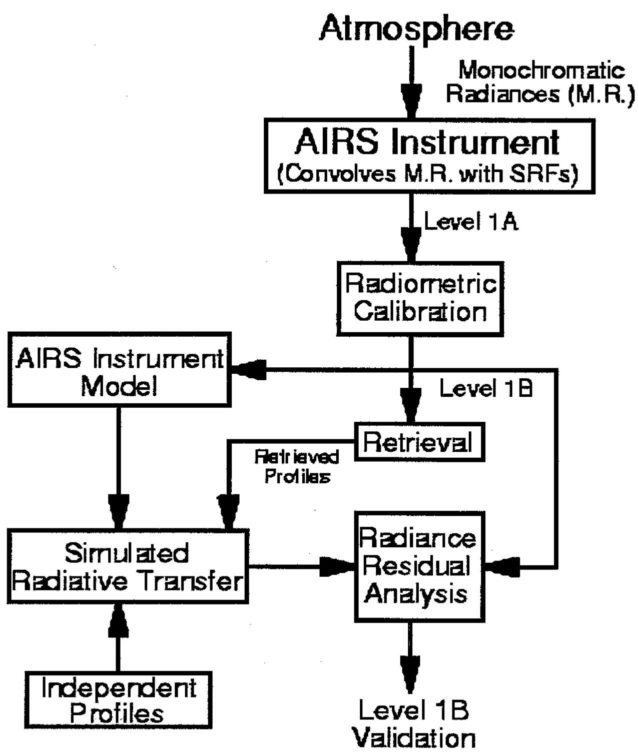

Figure 1. Top-level diagram of the AIRS Level 1B validation process.

1B validation, highlighting the comparison of computed and observed radiances in the ``Radiance Residual Analysis" box.

8.5. AIRS Instrument Spectral Model

AIRS has 2378 spectral channels that reside on 17 different linear detector arrays. Each detector serves as an exit slit for the AIRS grating spectrometer. AIRS uses 11 entrance slit apertures, which means that some arrays use the same entrance slit. The 2104 channels above 729 cm^{-1}, which are photo-voltaic (PV) detectors, consist of redundant pairs, giving a total of ~ 4500 channels. The detectors below 729 $cm^{-1}$are photo-conductive detectors with no redundancy.

The AIRS instrument spectral model has three basic components, the grating model, the SRF shape, and the entrance filter fringe positions, which combined together are used to simulate AIRS radiances and to build the fast model (AIRS-RTA).

Grating Model: As discussed in the AIRS level 1b ATBD, a relatively simple model based on the standard grating equation is able to model the AIRS wavenumber scale, at least on a per array basis. This model gives us the ability to predict the SRF centroids for each detector within an array given knowledge of the centroid of at least one detector on that array. The dependence of the grating model on both the instrument temperature, and focus, will be determined from ground calibration data. Once in orbit, up-welling radiances will be used to determine the absolute wavenumber positions of a sub-set of detectors. This information, combined with the grating model, will then allow us to determine the centers of every AIRS detector. Several arrays do not sense sharp, profile independent, features in the up-welling radiances, so we will have to use the grating model to transfer absolute calibration from one array to another. Since the focal plane is a rigid entity, this transfer should be highly accurate.

SRF Shape: The shape of the AIRS SRF is determined by a combination of the grating resolution, dispersion, size of the entrance slit apertures and the detector widths, and instrument scattering (important for the low-level SRF response). Extensive ground calibration tests provided reasonably accurate measurements of the shape of all ~ 4500 channels, within some signal-to-noise limitations for the long-wave arrays. A simple analytic model has been developed that appears to have sufficient accuracy to model all the grating spectrometer SRFs with just a few parameters per array. In addition, the change in the SRF width with focus has been measured during ground calibration. In the improbable case that AIRS suffers any significant change in focus during launch, the SRF widths will be estimated from the absolute wavenumber calibration via the grating model we have developed. It will be very difficult to calibrate the grating spectrometer SRF shape (SRF width, wings) in orbit. We will only determine if the AIRS radiances are consistent with our estimate of their on-orbit shape.

Fringes: The actual total SRF shape of AIRS has another component due to the existence of channel spectra (fringes) in the entrance slit aperture filters. Most of these 11 filters have some spectral regions containing interference fringes. These fringes have a nominal spacing (free spectral range) of 1.2 cm^{-1}, and a contrast of up to ±5% max. The fringe spacing is small enough to potentially impact all of the AIRS SRFs, which are in practice the entrance aperture transmittances times the ``pure" grating spectrometer SRFs. The positions of the peaks of the entrance aperture fringes are sensitive to temperature via the index of refraction of the filter's germanium substrate. The fringe peaks shift the equivalent of -9.96 microns/degK, while the SRF centroids shift –2.7 microns/degK. Since the width of the SRF is 100 microns (in focal plane coordinates), a change of 0.1 K in spectrometer temperature corresponds to a shift of the fringe peaks of 1% of the SRF. Consequently, the fringes will effectively be frozen relative to the SRFs once the AIRS instrument temperature has stabilized in orbit to within 0.1K of the setpoint of the spectrometer thermostat. The fringe positions relative to the SRF centroids will be inferred in orbit from the temperature dependence of the detector gains. (Basically, the

Because both the atmospheric spectroscopy and the AIRS instrument model (SRFs) are fixed in the AIRS-RTA, it cannot be used for some validation activities.

8.7. Level 1B Validation Approach

The basic approach to Level 1B validation is to use independent estimates of the atmospheric state to compute simulated AIRS observed radiances, and compare these with the observed radiances. Our overall goal is to improve the instrument, radiative transfer, and spectroscopic *models* in reasonable, understandable ways in order to reduce the radiance residuals. Since these models are largely independent of scan angle and cloud amount, this process will concentrate on nadir views of fields deemed very clear.

There is a high level of redundancy in the AIRS channels in the sense that many channels have very similar forward model weighting functions. The retrieval algorithms only use several hundred AIRS spectral channels, generally those with narrow weighting functions in regions where a single gas dominates the radiance. This leaves many

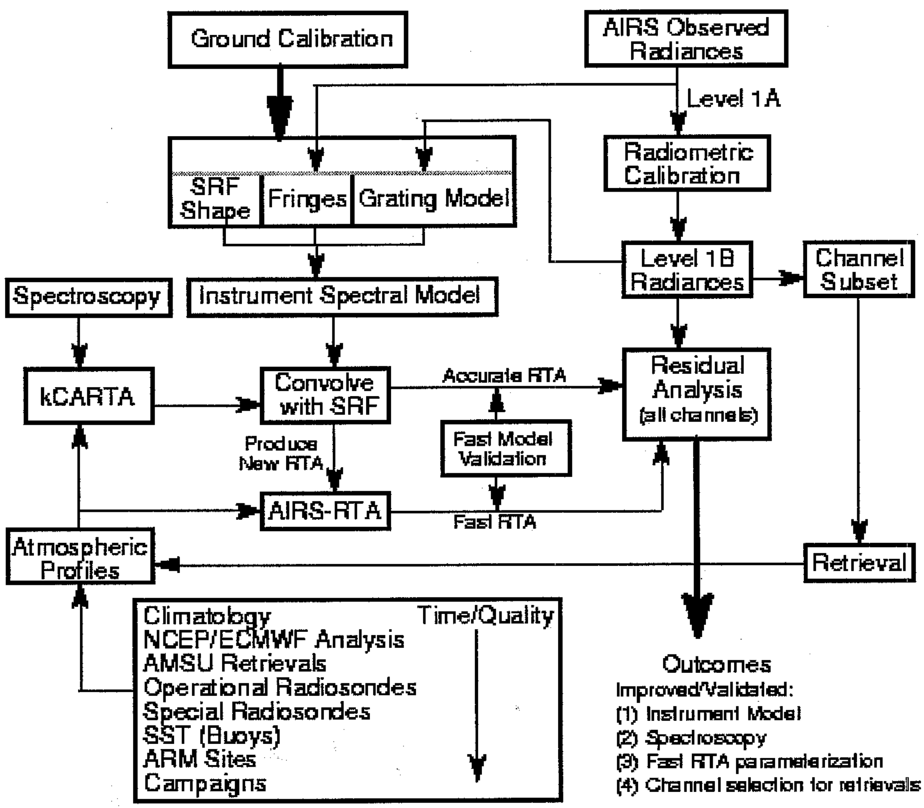

Figure 2. Detailed flow of Level 1B validation activities.

channels with somewhat wider weighting functions that probe the same part of the atmosphere as a combination of channels used in the retrieval.

detector gains see the modulation of the overall spectrometer transmission as the fringe peaks shift in wavenumber as the filter (and spectrometer) temperature is changed using the thermostat.) Detailed validation of the Level 1B radiances will therefore involve independent tests to determine if the in-orbit calibration of the fringe peak positions is sufficiently accurate.

8.6. Spectroscopy, kCARTA, AIRS-RTA

Comparisons of observed and computed AIRS Level 1B radiances depends on the accuracy of the AIRS spectral calibration and on the accuracy of the spectroscopy used in the computation of the simulated radiances. The accuracy requirements for the AIRS radiative transfer model are demanding, and will require the best available spectroscopy and line-by-line codes. In addition, the speed requirements for the Level 2 retrievals requires the use of a fast radiative transfer model (which we call the AIRS-RTA) that is based on parameterizations of atmospheric transmittances suitably convolved with the AIRS SRFs. This parameterization is discussed in some detail in the Level 2 AIRS ATBD.

The spectroscopy used in the AIRS-RTA is derived from kCARTA (kCompressed Atmospheric Radiative Transfer Algorithm), which is a monochromatic radiative transfer code based on compressed look-up tables of atmospheric transmittances. These look-up tables are created using a very accurate, but slow, line-by-line code developed at the University of Maryland Baltimore County, called UMBC-LBL. UMBC-LBL is a state-of-the-art line-by-line algorithm that includes features not found in other line-by-line codes such as P/R branch line-mixing in CO_2.

kCARTA will be used as the AIRS reference radiative transfer algorithm. kCARTA's primary purpose is for the generation and validation of the AIRS-RTA. However, it will also be useful for (1) early validation of the AIRS Level 1B radiances before the AIRS channel center frequencies have stabilized, (2) testing effects of new spectroscopy on AIRS simulated radiances for possible inclusion in the AIRS-RTA, and (3) providing AIRS radiances convolved with trial SRF models that are needed for Level 1B validation.

We independently validate the line-by-line algorithms by comparisons with new, better laboratory data when available. kCARTA is validated by comparisons to other line-by-line codes (GENLN2, LBLRTM) and by using it to compute validated radiances measured by the HIS/NAST-I instruments that fly on NASA's ER-2.

The AIRS-RTA is validated before launch by comparing radiances it produces to those computed with kCARTA, using an independent set of profiles (profiles other than those used to perform the regressions for the fast model parameters). The AIRS-RTA is dependent on a proper statistical selection of profiles used in the transmittance regressions (see the AIRS Level 2 ATBD for details). If comparisons of radiances computed with the AIRS-RTA disagree with kCARTA computed radiances when using profiles from actual AIRS retrievals, then our regression profile set must be re-examined.

Instrument errors, and to some extent spectroscopic uncertainties, will not be strongly correlated with a channel's weighting function. Given an independent assessment of the observed atmospheric profile, examination of the wavenumber dependence of the observed minus calculated radiances (the residuals) should allow us to detect patterns that correspond to different error sources. Analysis of these residuals will have to take into account our understanding of the errors associated with

(1) the independently measured atmospheric profiles,
(2) expected patterns in the uncertainty of the spectroscopy,
(3) expected error patterns in the (AIRS-RTA) parameterization,
(4) behavior of the instrument model if inadequately characterized, and
(5) uncertainties (and global variations) of atmospheric gases, such as CO_2, CH_4, and N_2O.

This process will start very early in the deployment of AIRS by comparing observed radiances with radiances computed using a climatology. This type of validation will only detect rather severe instrument errors and glaring software errors. As time progresses we will use ever better independent estimates of the atmospheric state as input to our computed radiances for comparison with the AIRS observed radiances. This includes profiles from (1) the NCEP or ECMWF analysis, (2) AMSU retrievals, (3) operational radiosondes, (3) special radiosondes launched during the time of AIRS overpasses, (4) ARM site data, and finally (5) intensive campaign *in situ* data. As the quality and amount of *in situ* profile data improves, our validation analysis will become more statistical in nature. For example, validation of radiances sensitive to lower tropospheric water vapor are problematic on a case-by-case basis due to the spatial/temporal variability of water and mismatches between radiosonde locations and the AIRS field-of-view. However, in a large statistical sample of these comparisons the random errors can be greatly reduced.

It may also be possible to validate the instrument model, and some relative aspects of the spectroscopy, by examining the residuals between radiances computed using the Level 2 retrieved profile and observed radiances. The wavenumber dependence of the residuals may highlight slowly varying spectroscopy errors. Instrument model errors (such as incorrect knowledge of the entrance slit aperture filter fringes) may also be inferred as follows. Perform a series of Level 2 retrievals, each using forward models with different placements of the entrance filter fringe peaks. Then examine the radiance residuals (computed for all channels) as a function of the fringe placement in the forward model and look for patterns that follow the known wavenumber dependence of the fringes. This process would be quite slow since it would most likely require use of kCARTA as the forward model. However, this may be the only way to validate the calibration of the fringe positions.

The AIRS channel center frequencies and the position of the entrance slit aperture filter fringes will be determined when AIRS is on-orbit. Consequently, the instrument model used in the AIRS-RTA must be re-computed post-launch once these quantities are determined. This process must be completed as quickly as possible to provide the Level 2 retrieval algorithms with an accurate forward model for the operational products. We will attempt to do as much Level 1B radiance validation as possible during this time frame (using kCARTA) so that the new AIRS-RTA will be produced quickly. The new AIRS-RTA will also include any improvements to the spectroscopy and fast model parameterization.

Figure 2 is a more detailed diagram of Level 1B radiance validation. It pictorially shows how the instrument model, spectroscopy, and atmospheric profile information flow into the main validation activity, the analysis of radiance residuals. Note that validation of the AIRS-RTA is done with kCARTA radiances convolved with the instrument SRF model, and does not require observed AIRS radiances. This step does need to use actual observed (retrieved) AIRS profiles to ensure that a proper statistical set of profiles was used in the development of the AIRS-RTA. The arrows leading to the instrument model from the Level 1A/1B data are calibration activities, and are included here to emphasize that the instrument model will not be complete until AIRS is in orbit.

9. Cloud-Clearing Algorithm Validation

9.1. Introduction

Cloud-cleared radiance is critical to retrieving geophysical parameters globally from AIRS observations. It is calculated algorithmically rather than observed directly. If the cloud-clearing algorithm performs correctly, the cloud-cleared radiance is the same as the upwelling radiance in cloud-free regions within an AIRS fooootprint. Nevertheless, the cloud-cleared radiance is strictly defined to be the output from the AIRS forward radiance model with the cloud contribution excluded. Note that this quantity is not defined for fully cloudy conditions; it cannot practically be calculated for cloudiness greater than 80%.

Cloud-cleared radiance and associated uncertaintities are a standard AIRS product. The accuracy of the radiance is affected both by instrumental noise (the noise associated with clear sky observations) as well as errors produced in the cloud-clearing procedure. The validation of the cloud-clearing algorithm or procedure is required to understand the uncertainties associated with retrieved quantities described in the sections which follow this one.

9.2. Cloud-Cleared Radiance Validation Requirement

Cloud-Clear Radiance Validation Uncertainty	**0.2 K**

Table 9. Cloud-cleared radiance validation requirement.

Single AIRS clear sky radiance spectra are predicted to have root-mean-squared radiance error of about 0.2K, with the largest errors in the channels with the lowest brightness temperatures. RMS errors in cloud-cleared radiances are predicted to be of the order of 1K, with the largest errors in window regions most affected by errors produced in the cloud-clearing procedure. Ideally, the validation source will have better than 0.1K accuracy.

9.3. Cloud-Cleared Radiance Validation Priorities

Validation Priorities	**Science Drivers**
1) Clear Ocean	Clear scene radiative balance.
2) Cloudy Land	Complex scene radiative balance.

Table 10. Cloud-cleared radiance validation priorities.

Cloud-cleared radiances will be most accurate over clear ocean scenes and least accurate over partially cloudy land scenes. Land conditions degrade the accuracy because of scene non-homogeneity. This not only reduces the accuracy of the cloud clearing procedure, but also makes it more difficult to define and measure the "true" cloud cleared radiances. Therefore, clear-sky ocean validation is the top priority, cloudy ocean is the second priority, clear land is third priority, and cloudy land is fourth priority.

9.4. Cloud-Clear Radiance Validation Methodologies

We will use both a direct and indirect method to validate cloud-cleared radiances. In the direct method, collocated cloud-cleared radiances will be compared to the AIRS cloud-cleared radiances.

9.4.1. Direct Validation of the Cloud-Clearing Algorithm

There are two sources of direct validation information. The first are the AIRS VIS / NIR observations. The procedure used be will be analogous to that described below for MODIS data. The AIRS VIS / NIR data will have poorer spatial resolution and signal-to-noise characteristics than the MODIS cloud fields, so will be used primarily to establish 'reasonableness' and test the cloud clearing validation procedure.

The major cloud-cleared radiance data validation source will be collocated MODIS observations for which at least one MODIS 1 km spot in the AMSU footprint (the retrieval footprint) is clear. We will examine the average of the AIRS cloud-cleared radiances in all channels within the spectral range of the MODIS channel. The MODIS channels to be used will either be window, temperature-sounding, or moisture-sounding channels. In completely clear cases, the radiance errors of the aggregate of many AIRS channels will be small, leaving a random error dominated by the MODIS channel noise. Any systematic error will stem from radiometric calibration differences between AIRS and MODIS. The radiometric bias between AIRS and MODIS will be determined by comparisons over a large number of clear-sky ocean observations. Ideally, this bias will be less than 0.1K. Under partially cloudy conditions, the dominant error in AIRS cloud-cleared radiances will come from the cloud-clearing process. These errors are highly correlated between channels and will not cancel when many AIRS channels are averaged together. The bias between AIRS and MODIS clear sky radiances will have to be subtracted out to obtain the bias errors in the AIRS cloud-cleared radiance due to the cloud-clearing process. Furthermore, the standard deviation of the errors of AIRS clear sky radiances will have to be removed to get the corresponding standard deviation of AIRS cloud-cleared radiances. It will also be of interest to compare the cloud-cleared radiance errors to the predicted values to gauge the predictive skill.

Similar procedures will be used for land scenes in both clear and partially cloudy conditions. The standard deviation between AIRS and MODIS radiances in clear conditions over land may be larger than over ocean because of effects of scene non-homogeneity. These will average out if both AIRS and MODIS respond equally to equivalent parts of the Earth's surface within the larger AIRS/AMSU/HSB retrieval footprint. The problem is more serious under partial cloud cover, because AIRS in effect averages over the clear portions of the 9 AIRS footprints within the AMSU footprint. The best approach is to average only MODIS clear spots and use this for comparison, though this will lead to differences in spatial sampling with the AIRS footprints. MODIS data will not be available immediately after launch. Within the first months of AIRS operations we will take advantage of the AIRS VIS / NIR channels over ocean during the day to identify AIRS spots which are completely clear. This will test our algorithm that indicates whether all nine AIRS spots in an AMSU footprint are clear. The VIS / NIR channels will also indicate cases of a individual clear AIRS footprints, in which case we will compare the cloud-cleared radiances for the nine footprint array to the radiances in the single clear case to estimate cloud-clearing errors. These are the easiest cases to cloud clear however, and, the algorithm should return the radiance in the clear spot as the cloud-cleared radiance.

9.4.2. Indirect Validation of the Cloud-Clearing Algorithm

Cloud-cleared radiances will be indirectly validated by examining the spatial coherence of the soundings themselves, especially over oceans. Errors in cloud-cleared radiances will show up as local inhomogeneities in retrieved quantities, especially sea surface temperature. The degree of homogeneity of soundings over adjacent clear ocean areas will be compared with those over adjacent partially cloudy areas to assess the degree to which errors are being made in the cloud-cleared radiances. The sea surface temperatures will also be compared to those produced by MODIS over clear and partly cloudy areas. Comparisons of clear areas will gauge a bias between AIRS and MODIS, to the extent that one exists.

9.5. Cloud-Cleared Radiance Validation Data Sets

Validation Priorities	**Necessary Data Sets**
1) Clear oceans, early in mission	1. AIRS VIS / NIR cloud mask
2) Clear oceans, MODIS operational	1. MODIS cloud mask.
3) Cloudy land	1. MODIS cloud mask; ARM CART site.

Table 11. Cloud-cleared radiance validation data sets.

We will need MODIS radiance values for cases considered by MODIS to be clear, as well as their time, latitude, and longitude, and satellite zenith angle. The angle and time should correspond well to that of AIRS because both are on the same satellite. We will also need values of MODIS sea surface temperatures. The radiance comparison for clear areas can be done early in the mission, even before the full retrieval algorithm is operational. This requires MODIS clear sky radiances as early as practical.

10. Sea Surface Skin Temperature Product

10.1. Introduction

Sea Surface Temperature (SST) is an important AIRS geophysical quantity to be validated. The magnitude of SST and its variability are basic to surface exchange processes in the ocean. The air-sea temperature difference influences surface moisture and sensible heat exchange, and cloud-surface radiation feedback is an important component of the surface energy balance. The World Climate Research Program has recommended that the accuracy of SST be known to within 0.3 K at 100 km spatial scales.

Recent climate experiments have shown that large temperature gradients can occur at the surface in the mid-ocean away from boundary currents or topographical features. Under conditions of low winds and relatively clear skies, the mid-ocean surface can be characterized by horizontal temperature gradients in excess of 1 K over scales of tens of kilometers [Hagan et al., 1997]. This has been related to large near surface in situ temperature gradients that develop from daytime heating of the upper ocean layer, combined with wave propagation, mesoscale ocean dynamics, variable surface winds, and radiative cooling under clouds [Walsh et al., 1998; Webster et al., 1996; Serra et al., 1997]. SST observations obtained at night can be equally complex as the near surface layer overturns under a cooler atmosphere.

Our goal is to validate the accuracy of the AIRS SST product at footprint, local and regional scales over the globe, for day versus night, at nadir and off-nadir viewing angles, and in clear versus cloudy conditions. Ocean validation sites that provide accurate, continuous time series of diurnal variability in SST are sparse. In order to build a robust statistical data set, our validation activities rely on as many high quality sources of SST information as possible. These sources are described in the following section.

10.2. Sea Surface Temperature Validation Requirements

SST RMS Uncertainty	0.5 K

Table 12. Sea surface temperature validation requirements.

10.3. Sea Surface Temperature Validation Priorities

Validation Priorities	Science Drivers
1) Cloud free ocean	1. Sea surface radiation budget 4) Evaporative and sensible heat exchange
2) Cloudy ocean	2. Hydrological Cycle 3. Cloud-surface radiation feedback
3) Day-Night Temperature Difference	1. Longwave radiative cooling.
4) Scan-angle dependence	1. Accurate use and evaluation of SST product

Table 13. Sea surface temperature validation priorities.

10.4. Sea Surface Temperature Validation Methodologies

The required accuracy for the AIRS SST retrieval product is essentially zero bias with a root-mean-square uncertainty of + 0.5 K. In order to attain this accuracy, our validation activities will lead to an understanding of essentially four classes of satellite SST retrieval error, these being: (1) biases introduced by residual cloud and /or aerosol contamination [Reynolds, 1988; Reynolds and Smith, 1994], (2) increased daytime scatter, especially in moist tropical conditions [Walton et al., 1998], (3) uncertainties associated with the regression of satellite spatial-mean brightness temperature against in situ "point" measurements at a depth well beyond the radiometric skin [Njoku, 1985], and (4) instrumental noise and calibration uncertainties (both satellite and in situ) [Njoku, 1985; Nalli, 1995]. The goal of our validation methodology is to develop an understanding of the errors in each of these classes, to separate sources of systematic trends and biases in the AIRS SST product. To accomplish this we will derive local and regional time and space match-ups between the SST product and in situ SST measurements as often as possible, using data which include shipboard radiometric measurements, drifting buoy measurements, fixed buoy data, and aircraft measurements. The following paragraphs summarize why each measurement type is needed and the measurement source.

With regard to the third class of error, one concern in using thermodynamic measurements for validation is the uncertainty of the temperature measurement associated with near surface mixing processes. In a recent comparison of global SST data sets, Hurrell and Trenberth (1999) point out that physical differences between skin and bulk temperature measurements may be a chief cause in the biases of satellite data sets. The MODIS ocean validation team is planning to minimize the effects of radiometric skin versus bulk temperature uncertainties by making FTIR surface emission measurements from ships (MODIS SST ATBD; Kearns et al., 2000, BAMS, in press).

Their plan is to deploy two to three M-AERI instruments. We have discussed the need for M-AERI measurements with Dr. Otis Brown (Principal Investigator for MODIS SST), and he has suggested we should collaborate in our validation activities.

One drawback in using specialized shipboard measurements such as M-AERI is the lack of frequency of measurements both in time and space for routine statistical monitoring and trend detection for AIRS. Hence, to help address the first two classes of retrieval error, we will rely on drifting buoy and fixed buoy SST measurements. Globally distributed drifting buoys have the advantage of sampling a wider range of temperature measurements and provide more opportunity for satellite and in situ match-ups under a variety of sampling conditions. Fixed buoys provide continuous, long-term records of SST variability and sea state for trend analysis.

We plan to use upper ocean temperature measurements from the WOCE Surface Velocity Drifter Program. This program deploys over four hundred satellite-tracked drifters annually in the tropics and southern ocean regions. Each drifter is equipped with a temperature sensor and air pressure sensor. The accuracy of the buoy temperature measurement is about 0.1-0.2 K. The buoy samples the water column at a depth between the first 20 to 40 cm of the surface, depending on wave conditions. The dispersion in temperature for these devices over a wide temperature range is typically about 1 K. For routine monitoring, the difference in the temperature measurement at depth relative to the skin temperature is within the range of acceptable uncertainty.

To obtain continuous SST time series at fixed sites, we plan to utilize buoy data from the TOGA TOA array, the Woods Hole Oceanographic IMET buoys, and the Scripps Institution of Oceanography Marine Observatory. In addition to SST measurements, these buoy systems log information about the state of the ocean and atmosphere, such as cloud cover, wind at the surface, relative humidity and air temperature. These parameters are useful for assessing the quality of the SST measurements. Two SIO buoys are positioned offshore from San Diego in the California Current, and the deployments of additional buoys at more northern sites are pending. The TOGA TAO array (about 70 systems) is located along the equatorial ocean. Three additional TOA buoys will be deployed over the next year (1N, 10N, 12N), and major sensor upgrades have been funded for the set of buoys located along 95 W. The IMET buoys support specific research activities at several locations. One buoy will be deployed next year for a three year period at about 19S, 85W near Chile. Two IMET buoys are currently being deployed in the Pacific, and two additional systems in the Atlantic are pending. The tropical Pacific DOE ARM site is another potential source of SST validation, the main drawback being that the in situ SST measurements are made close to the island. Funds are pending to support a very long-term buoy site at 15N, 51W in the western tropical Pacific.

As a fourth form of validation, radiometric measurements from aircraft data are needed sometime after the first six-nine months of AQUA operation. The aircraft observations are important since these can be used to better assess spatial variability within the satellite footprint and the variability between footprints. Nalli and Smith (1998) and Hagan and Nalli (1999) have demonstrated the ability to retrieve SST from aircraft radiometers with an accuracy approaching or better than 1%, for temperate to tropical water vapor conditions. Similar approaches to their instruments and methodology could be used in the aircraft experiments. At this time, we are not aware of any dedicated AQUA aircraft validation missions. It may be possible, however, to exploit other research activities in NASA such as the upcoming NASA CRYSTAL campaign in the tropical Pacific. Experiments involving ship and aircraft missions are also pending for fall, 2001, in the eastern tropical Pacific Ocean, under the auspices of CLIVAR.

We have described measurement techniques and capabilities that are currently available. However, in order to achieve a retrieval uncertainty which approaches the inherent capability of the instrument and forward radiance algorithm, high accuracy measurements of the near surface temperature gradient (e.g. the upper 10 cm of the ocean) are needed. The accuracy of sea truth comparisons and our understanding of the state of the ocean at the time of the in situ measurements can be improved with the capability to remotely profile the near surface layer. An initial engineering assessment indicates that the WOCE buoy design could be augmented for profiling purposes by adding additional temperature and pressure sensors. We have developed a plan to retrofit 50 WOCE drifters. The drifters will be ship-deployed at strategic ocean locations (TBD) as part of the normal operation of the WOCE drifting buoy program. Satellite transmission is provided through ARGOS. Because funding support to purchase, deploy and monitor the drifters is already in place, the augmentation of the drifters is relatively inexpensive.

In summary, our SST validation activities will depend on shipboard radiometric measurements (such as M-AERI) for point comparisons, drifting buoy measurements for more comprehensive statistical point comparisons, fixed buoy data for long term time series analyses, and aircraft measurements to understand spatial-mean brightness temperature effects. No specific costing has been carried out for the above activities, although estimates are currently in hand for retrofitting of the WOCE buoys, since this activity would need to be initiated as soon as possible.

10.5. Sea Surface Temperature Validation Data Sets

Validation Priorities	Necessary Data Sets
1. SST products in clear skies	Field Data Sets: Shipboard M-AERI WOCE Drifting Buoy Network PMEL, Woods Hole and SIO Fixed Buoys NASA Aircraft: TBD. Flights of opportunity using HIS, NAST-I, MAS and SSTR instruments one.
2) SST product in cloudy skies	Field Data Sets: Same as above. Aircraft Data Sets: TBD.
3) Satellite instrument cross validation	Satellite Data Sets: AVHRR, MODIS and ASTER.

Table 14. Sea surface temperature validation data sets.

Drifting Buoys
Source: WOCE.
Contact: Dr. P. Niiler.

Fixed Buoys
Source: PMEL.
Contact: Drs. M. McPhaden, Megan Cronin.

Fixed Buoys
Source: WHOI.
Contact: Dr. R. Weller.

Fixed Buoys
Source: SIO.
Contact: Dr. R. Rogers.

W. Pacific Tropical Site
Source: DOE-ARM.
Contact: Dr. T. Ackerman.

Shipboard
Source: M-AERI.
Contact: Drs. O. Brown, P. Minnett.

Aircraft NAST-I
Source: TBD.

Contact: TBD.

Aircraft SSTR
Source: TBD.
Contact: Dr. D. Hagan.

Aircraft HIS
Source: TBD.
Contact: Dr. H. Revercomb.

Satellite ASTER
Source: EOS.
Contact: Dr. F. Palluconi.

Satellite MODIS
Source: EOS.
Contact: EOSDIS, Michael King.

Satellite AVHRR
Source: NOAA.
Contact: Dr. N. Nalli, Satellite Active Archive at www.saa.noaa.gov

11. Land Surface Temperature Quantities

11.1. Introduction

The AIRS observations in the thermal infrared (TIR) atmospheric window, in the wavelength range 8μm -14μm, will be used together with AMSU-A microwave observations to estimate the Land Surface Temperature (LST). An accurate measure of the LST is essential to initialize, validate and verify climate models designed to assess the role of the land surface in governing seasonal-to-interannual variability at regional-to-global scales. The ability to monitor the land-surface energy flux will improve the understanding of the land-atmosphere climate interactions.

Interpretation of the AIRS retrieved LST is problematical due to the complicated nature of the land surfaces contained within the footprint of the AIRS and AMSU instrument. The footprint is likely to contain areas of bare ground, vegetation of various types and water in varying amounts and phases. The observed radiance is an average of the upwelling contributions of the different components. The horizontal and vertical structure of the vegetation can cause the relative proportion of vegetation and ground to depend upon the angle of the observation, which in turn can cause the apparent LST to change with the angle of observation.

The surface component emissivities are also retrieved. The surface emissivity is a physical property that relates the emitted radiance to the surface temperature - analogous to a radiative efficiency. Knowledge of the emissivity of land surface components is necessary for accurate determination of land surface temperatures. The emissivity of healthy vegetation is predictably high in the TIR (and may be assumed with relatively small error to be approximately 0.98), the emissivity of bare ground is another matter. The variation of emissivity of soils is dependent on constituents, surface texture and moisture content. The TIR emissivity has also been observed to be directional dependent for some soil surfaces.

11.2. Land Surface Temperature Validation Requirements

LST RMS Uncertainty	0.5 K
Emissivity	5 %

Table 15. Land surface temperature validation requirements.

11.3. Land Surface Temperature Validation Priorities

Validation Priorities	Science Drivers
1) IR Radiances in Cloud Free Columns	5) NMC model update 6) Energy Balance at Earth's Surface
2) Differential Temperatures Diurnal Drift & Day/Night Differential	• Energy flux atmosphere/ground • Climatology
3) MW/IR Retrieved LST & Emissivities Varying Cloud Condition/Moisture Content	2. Moisture transport 3. Surface-atmosphere interaction.

Table 16. Land surface temperature validation priorities.

11.4. Land Surface Temperature Validation Methodologies

The validation of the AIRS window channel radiances in cloud free columns and differential temperatures requires in situ observations at several ground sites where the tropospheric water vapor profiles and temperature profiles can be well characterized. MODIS has carried out radiative transfer simulations of the atmospheric transmission function for mid-latitude summer atmosphere over a lake surface at an elevation of 4 m above sea level in a dry region with emissivities greater than 0.95 for most of the 10-13 μm atmospheric window. These show that the difference between the radiance at the top of the atmosphere and the upwelling radiance at the lake surface is less than 1% for the wavelength range from 10.4 to 12 μm. (Given the high emissivity of land, these results for a lake surface may reasonably be extended to land surface).

MODIS has identified a location in Tibet, Nam Co (Tengri Nor), located at 30.40 N, 90.30 E as an excellent candidate site for in-situ post-launch validation. It is a lake frozen between November and May, located at 4718m above sea level, and of dimensions 80 km by 50km. MODLAND validation plans schedule field activity at this site in the second quarter of 2001, and AIRS should collaborate in this and similar activities for post-launch validation of AIRS window channel radiances.

AIRS in situ validation should employ instrumentation and support at the Department of Energy (DOE) Atmospheric Radiation Measurement Program (ARM) sites. The first field model of the Atmospheric Emitted Radiance Interferometer (AERI) is located at the Southern Great Plains (SGP) site in Oklahoma. Others are deployed at the Tropical Western Pacific (TWP), and North Slope of Alaska (NSA).

MODIS and ASTER are planning multiple field validations using AERI instruments, and AIRS will find beneficial cost saving in collaborating in these future activities. The following, from the original AIRS Validation Plan (Haskins et al., 1997) describes the AIRS plans to exploit the MODIS and ASTER validation efforts:

"Validation of sea surface temperature, land surface temperature, and land surface emissivity science products can be performed with a unique complement of instrumentation that has recently been developed at the University of Wisconsin-Madison. Accurate measurement of the infrared skin temperature and emissivity from a ground- or ship-based observing platform is possible. The instrumentation is an enhancement of the zenith viewing AERI system that allows for angle scanning in a plane over a 180 degree range of angles from nadir to zenith.

The land version of the scanning AERI instrument operated by the University of Wisconsin is currently in a prototype configuration installed in a mobile research vehicle. It is mounted on a telescoping hydraulic ram that allows the instrument to be raised about 16 feet above the ground for land surface viewing. This mobile instrument configuration has proven useful in obtaining grass and bare soil skin temperature and spectral emissivity measurements at the DOE-ARM Southern Great Plains site in September 1996 and snow surface temperature and emissivity measurements during January 1997 WINCE experiment in Madison. These observations have demonstrated the capabilities of this measurement technique and have been used to develop the tools to analyze this type of data. This mobile research vehicle can be used during campaigns in the continental United States for validation of AIRS surface temperature and emissivity products. These measurements should be coordinated with those planned for the MODIS instrument by working with the MODIS science team members responsible for land surface validation.

The fabrication of a dedicated land-AERI for routine and continuing validation of AIRS temperature and emissivity products during the AIRS operational period should be considered. Since Australia is likely to become a key ground truth site for the EOS PM-1 platform due to the temporal sampling characteristics of the platform orbit, consideration should be given to installation of a land-AERI at a ground site in central Australia. The installation and maintenance of this instrument would be handled in close collaboration with Dr. Mervyn Lynch of Curtin University, Perth, W. Australia who is intimately familiar with the AERI instrument and is already a part of the MODIS surface product validation activities. Consideration should also be given to establishing a land validation site on the Antarctic Plateau (e.g. Dome C, a French station at 74.5S, or Plateau station at 79S) in collaboration with NSF-funded investigators (Drs. Von Walden, U. Wisconsin and Steve Warren, U. Washington). These locations have cold, stable surface temperatures throughout the year with an infrared emissivity of near unity. The surface temperatures of the Antarctic Plateau are similar to those found at tops of clouds in the upper troposphere at lower latitudes. The emission in the longwave infrared window (800-1200 cm -1) because of the low column water vapor amounts (1 mm of precipitable water in summer and 0.3 mm in winter). In the clearest portions of the window, satellite instruments actually view the

> Antarctic surface with little emission from intervening gases. A downward viewing AERI can then provide accurate validation data on the surface emissivity and skin temperature without the need for expensive aircraft overflights. A lidar would be necessary to ensure that sub-visible cirrus and polar stratospheric clouds are not in the satellite field-of-view. Since a downward viewing AERI can accurately determine the surface skin temperature and its variability, this would allow radiometric validation of AIRS radiances over a cold target as well as validation of the land surface temperature product."

Of special interest for LST in situ validation is the downlooking Infrared Thermometer (IRT), already installed at multiple DOE ARM sites. This instrument is a ground-based radiation pyrometer that provides measurements of the equivalent black body brightness temperature of the scene in its field of view. The spectral sensitivity of this instrument covers the range 9.6-11.5 μm. AIRS validation of LST may benefit by procurement of one of these small, easily portable instruments for use at other convenient, uniform and typically non-vegetated sites such as Edwards AFB, Death Valley, White Sands and Railroad Playa.

A valuable adjunct to in situ validation will be vicarious comparison of AIRS LST and emissivities with retrievals by MODIS (Terra and Aqua platforms) and ASTER (Terra platform). Care will have to be taken to combine data from each instrument to create footprints that are spatially matched to the AIRS observations. ASTER has five TIR channels in the range 8-12 μm with a 90m spatial resolution. MODIS has 16 TIR bands in the range 3-15μm and its footprints are 1km resolution.

Potential field sites: Nam Co, Tibet; DOE ARM sites at SGP, TWP and NSA ice station.

11.5. Land Surface Temperature Validation Data Sets

Validation Priorities	Necessary Data Sets
1) IR Radiances in Cloud Free Columns	Field Data Sets: DOE ARM sites at SGP, TWP, NSA ice station; MODIS, ASTER dedicated validation site. Aircraft Data Sets: None.
2) Differential Temperatures Diurnal Drift & Day/Night Differential	Field Data Sets: Same as above. Aircraft Data Sets: None.
3) MW/IR Retrieved LST & Emissivities Varying Cloud Condition/Moisture Content	Field Data Sets: DOE ARM sites at SGP, TWP, NSA ice station. Aircraft Data Sets: None.
4) Vicarious validation	Satellite Data Sets: MODIS and ASTER.

Table 17. Land surface temperature validation data sets.

In Situ Data Sets: DOE ARM.

Ground-based Instrument Data Sets: DOE ARM.

Aircraft Data Sets: None

Satellite Data Sets: MODIS and ASTER.

11.6. Additional LST Validation Activities

AIRS-only field campaigns at Edwards AFB, CA, Death Valley, CA, White Sands, NV and Railroad Playa, NV.

11.7. Data Sources

Coordination with MODIS and ASTER science teams will allow the AIRS project to take advantage of the land surface emissivity and temperature databases created by those projects.

12. Temperature Profiles

12.1. Introduction

Atmospheric temperatures have the advantage, for validation purposes, of being horizontally smooth. This means that a precise collocation of validation observations is not as important as it is for some other AIRS parameters. Temporal variability is important at some levels. The atmosphere has two regions that experience diurnal variations: the surface layer over land and the stratosphere. The lower level varies because of heat transferred from the ground, and the stratosphere varies due to heating of the ozone molecules in sunlight. Atmospheric temperatures have been monitored for long periods of time and are important for weather forecasting. Because of this, there is an operational observing network in place that can be used to rapidly build a statistically significant sample. This network contains observations that are numerous, but not as accurate or as ideal for validation purposes as special measurements might be. The other extreme is to take carefully calibrated measurement designed to support the AIRS mission. The disadvantage of these measurements is the difficulty in obtaining a statistically meaningful sample and the cost of doing so. An intermediate approach is to use existing measurement facilities such as the radiosonde network or ARM sites to provide measurements at the time of the satellite overpass.

Conventional radiosondes provide the most comprehensive temperature measurements. But radiosonde temperatures are subject to some known errors. The radiosonde reports the temperature of a sensor that exchanges energy with its surrounding through radiative and convective processes. The accuracy the reported temperature depends on the accuracy to which the sensor reflects the temperature of the surrounding air. This, in turn, is determined by the time constant of the sensor and the extent to which the sensor temperature is determined by its radiative surroundings. Two types of sensors are widely used, one that is painted white and one that has a metallic coating. The white coating has a high reflectance in the visible, but is almost totally black in the infrared, so is less affected by solar radiation, but is subject to its infrared environment. The metallic coating is slightly more sensitive to solar radiation, but is almost independent of its infrared environment and has almost no error at night. The result is that the first sensor is more accurate in daylight and the second is more accurate at night. Although this is the major factor, countries have different instruments. Instruments differ, launch practices differ, processing differs, and some instruments add correction factors. As a result, the instruments have to be adjusted to a common reference before they are used. This is routinely done by the numerical prediction centers and a similar procedure will be used for AIRS. The AIRS procedure should be more accurate because a single instrument, the AIRS, will be used as a transfer standard to bring all the instruments to a common baseline.

There are other temperature sources such as buoys, surface air temperature observations, aircraft reports, the ARM sites, surface sounding instruments, and other satellite based measurements such as GPS and limb soundings. Our approach will be to combine as many of these as possible to fully characterize the atmosphere at a given location. Others, such as the aircraft reports over isolated areas such as the ocean, do not provide a complete vertical profile, but do provide wide coverage at selected altitudes. Plans for the AIRS validation are also discussed in the AIRS Validation Plan (Haskins et al., 1997).

12.2. *Temperature Profile Validation Requirements*

Surface to 700 hPa	1.0 K in 1 km layers
700 to 30 hPa	1.0 K in 3 km layers
30 to 1 hPa	1.0 K in 5 km layers
1 to 0.001 hPa	3.5 K in 5 km layers

Table 18. Temperature profile validation requirements.

12.3. *Temperature Profile Validation Priorities*

Validation Priorities of Atmospheric Regime	Science Drivers
1) Surface over ocean and land	1. Radiative balance and surface energy flux 2. Determination of surface emissivity 3. Long term trends in surface air temperature
2) Mid and upper tropospheric temperatures	1. Radiative balance 2. Atmospheric dynamics
3) Upper atmospheric temperatures	7. Radiative balance 8. Atmospheric dynamics

Table 19. Temperature profile validation priorities.

12.4. *Temperature Profile Validation Methodologies*

Temperature retrievals are most difficult and least accurate in regions of vertical gradients, such as the region near the surface and the region near the tropopause. As mentioned earlier, the surface is also one of the two regions that experience large diurnal temperature variations (up to 30 K for the surface). This diurnal variability makes surface retrievals more difficult to validate than the those in the free atmosphere. But at the same time, the lowest region of the atmosphere has the advantage of having a large amount of data to use for validation. This region will be evaluated by comparing the AIRS retrievals with radiosondes that are coincident in time, with hourly surface observations, with observations from the ARM sites, and with aircraft reports near airports. Most special observations include temperature data. Data are readily available at the lowest levels.

Middle tropospheric temperatures are available from radiosondes, including routine ones, special ones like at the ARM sites, radiosonde launches designed to coincide with the time of the satellite passage, and aircraft reports. The aircraft reports can give a profile near airports, but should be used with an analysis because the high level observations occur some distance from the airport. The analysis near an airport should be highly influenced by the large number of observations at that location. The aircraft reports also give single level data over commercial air lanes. Operational radiosondes are launched at 0000Z and 1200Z and coincide with the satellite overpass only at two longitudes. A few sites launch at 0600Z and 1800Z (these will never be under AIRS with its 1:30 AM and PM equator crossings). Special radiosonde launches will be required to increase the sample size at other longitudes to provide global coverage. With global coverage for a limited period, the information of just the observational network can be established. The usefulness of the dedicated observations at the ARM sites will be compromised if the data are not time coincident with the satellite overpass. Special launches to support the validation can greatly enhance the contribution these sites make to the validation effort.

The upper level temperatures are the most difficult in terms of the availability of validation data. Radiosondes ascend to about 10 mb, or 30 kilometers and many don't reach this level. Rocketsondes go to 85 or 65 kilometers, depending on the type, and number a total of about 100 per year. The most readily available source of data for this region is indirect measurement. These have the problem that, being retrievals, may be subject to some of the same errors as the AIRS retrievals even though they differ in significant ways. The GPS can provide temperatures up to 60 kilometers, but they become noisy after 45 kilometers (1 mb.). Limb sounding instruments such as HALOE and SAGE can provide measurements with sharp vertical resolution and low horizontal resolution in contrast to the AIRS which has less vertical resolution but better horizontal resolution.
To remove this limitation, it is necessary to extend the top of the atmosphere with realistic data.

With the type of data available, there are three approaches to validation. One is to provide as much information from as many complementary sources as possible to specify the complete profile. This is more important for tuning than it is for validation because the entire profile needs to be specified before the radiances that are required for tuning can be calculated. But a complete profile is required to evaluate the vertical structure of the retrieved temperature profiles. Second, there are other areas where data are available only at one or a few levels. When these data are in areas that are otherwise void of validation data, they are valuable. Finally, the numerical models provide information on a global scale. While these data are influenced by the model used for their generation, they have the advantage of being available everywhere. Each of these types of data can provide information to validate features not possible with the data from the other sources.

The validation will be stratified by the expected quality of the retrieval. Retrievals in clear areas are more accurate than those in cloudy areas. Retrievals over oceans are more accurate than those over land. The accuracy also depends on the latitude and season. There are also quality flags that are generated by the processing. The validation will ascertain the extent to which these flags actually provide information about the quality of the retrieval.

12.5. Temperature Profile Validation Data Sets

Validation Priorities of Atmospheric Regime	Necessary Correlative Data Sets
1) Lower atmosphere temperatures	4. Radiosondes, hourly surface observations, ARM data, buoy data, surface based profiler data
2) Mid tropospheric temperatures	3. Radiosondes, commercial aircraft reports, ARM data, surface based profiler data, other satellite retrievals. 4. Time coincident radiosonde launches
3) Upper atmospheric temperatures	9. Radiosondes, rocketsonde data, GPS retrievals, limb sounding data.

Table 20. Temperature profile validation data sets.

12.6. Additional Temperature Profile Validation Activities

There will be special measurements made to support other EOS instruments and other AIRS parameters such as water vapor. Temperatures are required for these measurements and will be incorporated into the AIRS validation. Measurements that are time coincident with the satellite overpass are especially valuable. Time coincident radiosonde launches from the ARM sites and the conventional radiosonde sites are required.

13. Water Vapor Quantities

13.1. Introduction

A number of factors complicate the validation of water vapor. First, it is more inhomogeneous than similar meteorological fields such as temperature. This makes difficult the intercomparison between profile measurements (from radiosondes) or planar measurements (from aircraft-borne lidars) and the AIRS/AMSU/HSB retrieval, which incorporates radiation from a 45 km diameter area. Secondly, water vapor has a wide dynamic range, with mixing ratios varying by two orders of magnitude within the troposphere. (Stratospheric humidity is two orders of magnitude lower still, but its validation is not an AIRS priority.) Finally, upper tropospheric water vapor distributions are poorly understood. This makes comparisons with climatologies difficult or impossible. At the same time upper tropospheric water vapor is of great scientific interest, making its validation important.

13.2. Water Vapor Validation Requirements

Surface to 100 hPa	15 % in 2 km layers

Table 21. Water vapor validation requirements.

13.3. Water Vapor Validation Priorities

Validation Priorities of Atmospheric Regime	Science Drivers
1) Upper Troposphere	• Planetary radiative balance • Convective control of upper troposphere
2) Moist Lower Troposphere Profile	• Global water vapor loading • Radiative balance
3) Dry Lower Troposphere Profile	• Radiative balance.
4) Water Vapor Integrated Column	• Global water vapor loading.

Table 22. Water vapor validation priorities.

13.4. Water Vapor Validation Methodologies

The following methodologies refer to the prioritized list in the table above.

1) Upper Troposphere

Upper tropospheric humidity has received enormous scientific attention in the past decade. Much of the debate about global warming concerns the degree to which upper tropospheric water vapor modulates the planetary radiative balance. Our observational understanding of upper tropospheric water vapor is currently very limited.

The difficulty in validating the AIRS retrieved upper tropospheric water vapor starts with validation of the AIRS Level 1b radiances. Although Level 1b validation may be successful for many AIRS channels, we expect it will be quite difficult to validate channels sensitive to upper tropospheric humidity. This will affect a large number of the AIRS M3, M4a and M4b array channels. Even if their weighting functions peak at lower altitudes, they have tails at higher altitudes where the radiosonde measurements are extremely inaccurate. Upper tropospheric water radiances are (1) quite low (220 -250K), and (2) offset significantly from the AIRS OBC temperature of 308K and thus are more subject to detector non-linearity errors than other channels. The combination of these problems will make validation of upper tropospheric water vapor radiances difficult. However, the importance of these channels for global climate change and outgoing longwave radiation (OLR), and the fact that AIRS will provide measurements of this key quantity that are far better than existing techniques, provides the impetus for a significant validation effort.

The are two approaches to this validation of AIRS upper tropospheric water retrievals. The first requires the coordinated underflight of several airborne instruments. A similar activity occurred on the CAMEX-3 calibration flight (McMillan, 1998). The primary observations are high-resolution infrared spectra from the NAST-I instrument flown on the high altitude ER-2, and humidity observed by the LASE instrument onboard a DC-8 in the middle troposphere. These flights should occur over a tropical ocean, preferably during cloud-free conditions. This set of observations will provide a simultaneous check on the amounts of water vapor present, and the atmospheric spectral response.

Another potential upper tropospheric water vapor validation activity utilizes the Raman lidar currently operational at the ARM/CART Great Plains site. An overflight of the lidar with NAST-I on the ER-2 will provide information similar to that available from the CAMEX-3, with the added possibility of multiple overpasses and considerable cost savings. The lidar has the additional advantage of very high signal-to-noise ratios at night.

Potential campaign sites: Caribbean / Atlantic, Western Pacific.
LASE URL: http://asd-www.larc.nasa.gov/lase/ASDlase.html
CART Raman Lidar URL: http://www.arm.gov/docs/instruments/static/rl.html

2) Moist Lower Troposphere

Most atmospheric water vapor loading occurs in the tropics and the summer hemisphere. An extended set of research-quality radiosonde observations in such regions will provide an important correlative data set. These radiosondes must be characterized by near-simultaneity with the EOS-Aqua satellite overflights to avoid diurnal biases. They must also have significantly better error characteristics than the 15% AIRS water vapor validation criteria.

Though operational radiosondes are relatively reliable as a water vapor validation source, they have one very significant shortcoming: a lack of simultaneity with the EOS-PM spacecraft virtually everywhere except the Middle East and northern Europe. This is because the spacecraft orbit's local times of 1:30 AM and 1:30 PM place it over radiosonde-sparse regions when radiosondes are launched at 0 GMT and 12 GMT. This implies that a set of dedicated radiosondes must be launched under the EOS-PM spacecraft at time other than 0 GMT and 12 GMT. Some regions where this might be done are the southern United States, the Amazon, the Western Pacific or tropical Australia.

Moist lower tropospheric conditions can be monitored over significant time periods with the Raman lidar at the ARM / CART Great Plains site.

Potential campaign sites: ARM/CART Midwest Site during summer and Western Pacific Site year-round, the Amazon Basin, Caribbean, Southern Florida.

3) Dry Lower Troposphere

Large regions of the globe are characterized by small amounts of water vapor in the troposphere. These include polar regions, deserts, area of high topography, and midlatitude continents during winter. A high-quality radiosonde data set as described for the moist lower troposphere will be needed in these regions to ensure that the AIRS methodology is effective there.

As with the moist lower troposphere, dedicated radiosonde launches will provide useful validation information in drier parts of the lower troposphere. Operational radiosondes are less sensitive to lower humidity, however, so dedicated, more sensitive radiosondes will provide useful information in many regions where relative humidity is consistently low.

The Raman lidar at the ARM/CART facility will provide important information about the dry troposphere during winter.

Potential campaign sites: ARM/CART Barrow Facility, ARM/CART Midwest Site in winter, continental U. S. during winter.

4) Validation of Total Water

There are a number of sources of total water vapor, including observations from surface-based microwave radiometers, and integrated amounts from radiosondes and Raman lidars. These will be exploited in the first several months of operation of the AIRS, AMSU and HSB instruments (all of which provide estimates of integrated water vapor).

After nominal operation of the AIRS / AMSU / HSB instrument suite has begun, MODIS and AMSR will make total water vapor measurements. All five instruments will make coincident observations with fields of views varying from a few kilometers to a few tens of kilometers. The vicarious cross-validation of integrated water vapor from most of the instruments on the Aqua platform will be an important part of the overall Aqua validation activities.

13.5. Water Vapor Validation Data Sets

Validation Priorities	Required Correlative Data Sets
1) Upper Troposphere	Aircraft: Tropospheric mixing ratio distribution from LASE instrument on the DC-8, under clear-sky conditions over ocean. Simultaneous high-resolution spectra from NAST-I on ER-2. In Situ: Collocated radiosondes and dropsondes for temperature profile information
2) Moist Lower Troposphere Profile	Tropical site ARM / CART Raman lidar
3) Dry Lower Troposphere Profile	ARM / CART Raman lidar
4) Water Vapor Integrated Column	MODIS, AMSR ARM / CART Raman lidar, microwave radiometer.

Table 23. Water vapor validation data sets.

14. Ozone Total Column and Profile Validation

14.1. Introduction

Ozone total column and profile measurements rely on separate sources for comparisons and validation. The two quantities are not derived accurately or reliably from the same sources. The integration of profile measurements usually underestimates total column due to the lack of tropospheric profile information, and in comparison the information content for high vertical resolution profile information is not obtainable from nadir remote sensing column measurements. The critical scientific objectives for AIRS will be to measure an accurate total column ozone and tropospheric ozone ("profile" or "column"). The vertical resolution in the stratosphere is less likely to be useful except in general data assimilation.

14.2. Ozone Validation Requirements

Total Ozone Column	.03 atm-cm
Surface to tropopause	30%
Tropopause and above	20 %

Table 24. Ozone validation requirements.

14.3. Ozone Validation Priorities

Validation Priorities of Atmospheric Regime	**Science Drivers**
1) Troposphere	7) Indicative of oxidizing potential of lower atmosphere
2) Total column ozone	• Trends in total ozone during recovery phase following decline in stratospheric chlorine loading
3) Stratosphere	• Trends in profile as stratospheric ozone recovers

Table 25. Ozone validation priorities.

14.4. *Ozone Validation Methodologies*

The following methodologies refer to the prioritized list in the table above.

1) Troposphere

Several techniques have been developed to infer tropospheric column ozone. This involves comparing total column ozone measurements with ozone profiles or ozone columns for the stratosphere, subtracting the two (large numbers!) for the residual column. These are calculated over time scales of several days up to monthly mean values. It requires TOMS data.

2) Total column ozone

Direct comparison on a daily basis with TOMS and ground-based Dobson spectrometer measurements made within a few hours of each other. The AIRS data should be used to estimate cloud coverage and clear conditions selected.

3) Stratosphere

The integrated column through the stratosphere is difficult to reconcile with sporadic profile measurements, but comparisons with SAGE-III and Lidar measurements will form the basis of any validation.

14.5. *Ozone Validation Data Sets*

The following dataset refer to the prioritized list in the table above.

1) Troposphere

In Situ Data Sets: Correlative radiosondes and dropsondes at times of aircraft flights.

Ground-based Instrument Data Sets: None.

Aircraft Data Sets: High-resolution infrared spectra from instrument on ER-2 (e. g. NAST-I). Upper tropospheric humidities from lidars (e. g. LASE).

Satellite Data Sets: None.

2) Total column ozone

In Situ Data Sets: None

Ground-based Instrument Data Sets: Dobson spectrometer network

Aircraft Data Sets: None

Satellite Data Sets: TOMS

3) Stratosphere

In Situ Data Sets: Balloon-borne profiles from in situ and infrared sensors

Ground-based Instrument Data Sets: LIDAR

Aircraft Data Sets: None

Satellite Data Sets: SAGE-III

14.6. Secondary Ozone Validation Activities

Vicarious calibration with other satellite instruments.

14.7. Ozone Data Sources

http://toms.gsfc.nasa.gov/ : TOMS home web page

14.8. Ozone References

World Meteorological Organization, Global Ozone Research and Monitoring Project - Report No. 44, Chapter 4, Ozone Variability and Trends, 1999.

http://toms.gsfc.nasa.gov/ : TOMS home web page

http://www.atmosp.physics.utoronto.ca/GOMAC/abstracts/AtmMes/newchurch_wed_14_40
.html abstract of a talk comparing Umkehr to SAGE

http://eospso.gsfc.nasa.gov/atbd/sagetables.html SAGE-III ATBDs

http://www-arb.larc.nasa.gov/sage3/ SAGE-III Home Page

15. Cloud Properties

15.1. *Introduction*

Clouds are an important element of Earth's weather and climate systems and its hydrologic cycle, yet clouds are poorly understood. This is why the AIRS cloud products are so important and it is also why validation will be difficult. Validation of the AIRS cloud products will involve data at IR, microwave, and visible wavelengths. It should be kept in mind that, particularly in the case of cloud fraction, the definition of a cloud can be a function of wavelength. For example, the visible cloud fraction is expected to be systematically different than the IR cloud fraction.

15.2. *Cloud Validation Requirements*

(From Chahine *et al.* 1991.)

Cloud Fraction	5% absolute, 2.5% relative
Cloud-Top Height	500 m absolute, 250 m relative
Cloud-Top Temperature	1 K absolute, 0.5 K relative

Table 26 Cloud validation requirements.

15.3. *Cloud Validation Priorities*

Validation Priorities of Cloud Properties	**Science Drivers**
1) Cloud-Top Temperature	8) Planetary radiative balance 9) Information on cloud type and distribution
2) Cloud Fraction	• Planetary radiative balance • Horizontal cloud distribution
3) Cloud-Top Height	4. Information on cloud type and distribution

Table 27. Cloud validation priorities.

15.4. Cloud Validation Methodologies

The following methodologies refer to the prioritized list in the above table.

1) Cloud-Top Temperature

The infrared radiative temperature of a cloud is a direct measure of one component of Earth's energy loss to space, while the true physical temperature of a cloud-top provides information on the cloud altitude and phase (ice or liquid). Knowing both the radiative and physical temperature implies knowledge of the cloud emissivity, which is related to cloud optical depth and microphysical quantities.

AIRS cloud-top radiative temperatures (the product of physical temperature and emissivity) will be validated primarily by a comparison to MODIS cloud products and broadband AVHRR/CLAVR data at 4, 11 and 12 microns (AVHRR channels 3, 4, and 5, respectively). The noise equivalent temperature for these AVHRR channels is expected to be near 0.12 K for a 300 K target. Note that AIRS retrieves cloud temperature on a 13.5 km scale at nadir, while MODIS and AVHRR resolutions are near 1 km, allowing us to validate as a function of scene variability within the AIRS footprint. A secondary validation data sources is the TOVS instrument, which also provides a direct measure of radiative temperatures in the infrared. MODIS is chosen as a primary validation data set because of its spatial and temporal collocation with AIRS. AVHRR is also used because of its proven ability to provide data in a timely fashion. Aircraft-borne IR sensors, such as NAST-I, may also be used for validation, but the limited spatial sampling of aircraft makes interpretation difficult.

The comparison among instruments will be made for observations co-located in space and time wherever possible. Comparisons of quantities averaged into location and local time-of-day bins can also be made if insufficient simultaneous data are available—as is likely for AVHRR data.

Validation of AIRS retrieved physical temperature is more difficult, and will be attempted by comparison to in-situ and statistical data. Direct measurements by temperature probes onboard aircraft under-flying the Aqua spacecraft are the most direct validation possible, but the comparison can only be made in regions known to be horizontally uniform on a scale of 10 km. Alternatively, the statistics of AIRS physical versus radiative cloud temperature (a measure of cloud emissivity) as a function of cloud temperature or height, can be compared to cloud models. (In this case, cloud temperature or height is used as a proxy for cloud type, and the assumption is made that, on average, trends in cloud emissivity should follow trends in cloud type.)

Software Tools Needed
To carry out the above analyses, the ability to make scatter-plots of AIRS retrieved quantities versus those from other instruments is needed, as well as the ability to calculate correlation coefficients and linear fits to the plots. In addition, it should be possible to subset data by latitude, longitude, surface local time, surface type, look angle, AIRS

cloud emissivity, AIRS number of cloud layers, day/night, and the VIS / NIR variability indices. The ability to do some spatial averaging of AVHRR data, as well as the ability to multiply/divide AIRS temperatures by cloud emissivity before analysis is also useful. For comparing non-simultaneous observations, the software should be able to average data sets into bins of location and time before performing the above functions.

2) Cloud Fraction

Given that clouds vary significantly on scales smaller than the AIRS IR footprint (~13.5 km at nadir), it is important to know the fraction of an IR field of view occupied by clouds. Current NOAA sounders (TOVS, ATOVS) report an "effective IR cloud fraction", which is a single number involving the cross sectional area of clouds in the field of view and the emissivity of those clouds, for all cloud layers present. MODIS intends to provide a similar product. AIRS will improve upon this by retrieving individual properties for several cloud layers, and trying to separate emissivity effects from the areal extent of clouds. Even with the emissivity effect taken into account, it should be kept in mind that the IR cloud fraction need not be identical to the cloud fraction as seen at visible wavelengths.

The primary validation of the AIRS cloud fraction will therefore be made by a comparison to other IR instruments—the MODIS and TOVS cloud fractions. (It may be necessary to limit the comparison with MODIS to night conditions to guarantee that visible wavelengths are not being used.) To make this comparison, the AIRS fraction must be multiplied by the AIRS-retrieved emissivity (to make an "AIRS effective fraction"), in areas where only one cloud layer exists (as determined by either observer reports, the number of cloud layers retrieved by AIRS, or AVHRR data). Once validated on single cloud layers, similar comparisons can be made in the presence of multiple clouds, but the limitations of the TOVS system make this comparison somewhat ambiguous. While the collocation of AIRS and MODIS products allows them to be compared directly, the comparison of AIRS to TOVS will have to be in a statistical sense, since the instruments are on different platforms.

Secondary validation will involve instruments at visible wavelengths. Though the true cloud amount may be different for visible and IR instruments, one would expect that the trends seen in comparing the TOVS IR cloud fraction with AVHRR/CLAVR visible cloud fractions would be repeated when the AIRS effective fraction (true fraction times emissivity) is compared with MODIS visible, AVHRR visible, or the AIRS VIS / NIR cloud fraction. Furthermore, one would expect the AIRS true cloud fraction to more closely match the visible cloud fraction than the AIRS "effective cloud fraction".

As with cloud temperatures, the comparison among different instruments will be made for simultaneous observations whenever possible, but averaged values sorted by location and local time can also be used.

Software Tools Needed

To carry out the above analyses, the ability to make scatter-plots of AIRS cloud fraction (optionally multiplied by the AIRS retrieved emissivity) versus those from other instruments is needed, as well as the ability to calculate correlation coefficients and linear fits to the plots. In addition, it should be possible to subset data by latitude, longitude, local time, surface type, look angle, AIRS cloud emissivity, AIRS number of cloud layers, day/night, and the VIS / NIR variability indices. The ability to do spatial averaging of the various data sets is also necessary (for example, AIRS data must be averaged to match TOVS resolution, while AVHRR and MODIS data must be averaged to match AIRS resolution). Finally, to support statistical comparisons, the software should be able to average data sets into bins of location and time before performing the above functions.

3) Cloud-Top Height

The height of clouds (presumably closely related to cloud temperature) most directly tells us about the vertical distribution of clouds, and is also useful for dividing clouds into types (cirrus, for example). Global-scale, statistical validation of the AIRS cloud-top height is by a comparison to TOVS and ISCCP DX retrieved cloud height, though neither of these provides the 500 m accuracy desired. As with cloud fraction, the ability of AIRS to distinguish multiple cloud layers must be accounted for when making the comparison. Once operational, the MODIS cloud-height product can also be used.

More accurate validation data sets are cloud-top observations from either ground- or aircraft-based LIDAR, and observer reports from aircraft. The limited spatial extent of these data sets, however, means they can only be used as spot checks. A useful internal consistency check of AIRS cloud-top height is to compare the liquid water profiles retrieved as a microwave research product with the IR-based cloud height.

Software Tools Needed

As with the other cloud properties, validation requires the ability to make scatter-plots of AIRS cloud height versus those from other instruments, as well as the ability to calculate correlation coefficients and linear fits to the plots. In addition, it should be possible to subset data by latitude, longitude, local time, surface type, look angle, AIRS cloud emissivity, AIRS number of cloud layers, day/night, and the VIS / NIR variability indices. The ability to do spatial averaging of the various data sets is also necessary.

To make the consistency check with the AIRS microwave product, it is necessary to generate a microwave cloud-top height, by allowing the user to set a threshold liquid water abundance, above which a cloud is presumed to exist. The highest-altitude layer meeting this threshold is taken to be the microwave cloud-top height.

15.5. Cloud Properties Validation Data Sets

Below are listed data sets organized by the priority of the product they validate. The table below presents a prioritized list of the validation data.

1) Cloud-Top Temperature

In Situ Data Sets: See Aircraft Data.

Ground-based Instrument Data Sets: None.

Aircraft Data Sets: In-situ temperature probes, NAST-I.

Satellite Data Sets: MODIS, AVHRR/CLAVR, TOVS.

Computer Models: Cloud emissivity calculations as a function of cloud-type.

2) Cloud Fraction

In Situ Data Sets: None.

Ground-based Instrument Data Sets: None.

Aircraft Data Sets: None.

Satellite Data Sets: MODIS, TOVS, AVHRR/CLAVR.

Computer Models: None.

3) Cloud-Top Height

In Situ Data Sets: None.

Ground-based Instrument Data Sets: LIDAR.

Aircraft Data Sets: LIDAR, Observer Reports.

Satellite Data Sets: MODIS, TOVS, ISCCP DX.

Computer Models: None.

15.6. *Cloud Validation Methodologies*

Primary Data Sets	Validation Use
MODIS	Temperature, Fraction, Height
AVHRR	Temperature, Fraction
CLAVR	Temperature, Fraction
TOVS	Temperature, Fraction, Height
A/C Temperature Probe	Temperature
LIDAR (a/c-based)	Height

Secondary Data Sets	Validation Use
LIDAR (ground-based)	Height
ISCCP DX	Height
A/C Observer	Height
Cloud Emissivity Model	Temperature
NAST-I	Temperature

Table 28. Primary and secondary cloud validation data sets.

15.7. *Cloud Properties Validation Data Sets*

Chahine *et al.* 1991. AIRS Science and Measurement Requirements. JPL Document D6665, Rev. 1 (September 1991).

15.8. *Cloud Properties Validation Data Sets*

Aircraft in-situ temperature probes
Validation Use: Cloud-top temperature.
Source: Validation field campaigns.
Contact: TBD

Aircraft observer reports
Validation Use: Cloud-top height.
Source: Validation field campaigns.
Contact: TBD

AVHRR
Validation Use: Cloud-top temperature, cloud fraction.
Source: NOAA.
Contact: Satellite Active Archive at www.saa.noaa.gov.

CLAVR
Validation Use: Cloud-top temperature, cloud fraction.
Source: NOAA/NESDIS.
Contact: Larry McMillin.

Cloud Emissivity Model
Validation Use: Cloud-top temperature.
Source: UCSB, JPL.
Contact: Catherine Gautier, Mark Hofstadter.

ISCCP DX
Validation Use: Cloud-top height.
Source: ISCCP.
Contact: www.isccp.giss.nasa.gov (monthly means), TBD (realtime).

LIDAR (Ground-Based)
Validation Use: Cloud-top height.
Source: ARM Program.
Contact: TBD

LIDAR (Aircraft-Based)
Validation Use: Cloud-top height.
Source: Validation field campaigns.
Contact: TBD

MODIS
Validation Use: Cloud-top temperature, cloud fraction, cloud-top height.
Source: EOS.
Contact: EOSDIS, Michael King.

NAST-I
Validation Use: Cloud-top temperature.
Source: TBD.
Contact: TBD.

TOVS
Validation Use: Cloud-top temperature, cloud fraction, cloud-top height.
Source: Goddard.
Contact: Joel Susskind.

16. Visible and Near-IR Products

16.1. Introduction

The AIRS instrument carries four visible/near-IR (VIS / NIR) sensors, providing diagnostic information to the IR retrieval. The basic VIS / NIR products to be validated at launch are the Level 1b radiances, the cloud and low-cloud detection diagnostic, and the scene variability diagnostic quantities. Only the radiances have a requirement associated with them: validation of the two diagnostics is primarily an assessment of their accuracy.

16.2. VIS / NIR Validation Requirements

Radiance	20% absolute, 5% relative
Cloud/Low-Cloud Detection	None
Scene Variability Indices	None

Table 29 VIS / NIR validation requirements.

16.3. VIS / NIR Validation Priorities

Validation Priorities of VIS / NIR	**Science Drivers**
1) Radiance	10) Serves as the basis for all VIS / NIR products, including Research Products
2) Cloud/Low-Cloud Detection	• Diagnostic for AIRS retrievals • Cloud distribution
3) Scene Variability Indices	5. Diagnostic for AIRS retrievals

Table 30. VIS / NIR validation priorities.

16.4. VIS / NIR Validation Methodologies

The following methodologies refer to the prioritized list in the above table.

1) Radiance

Primary validation of VIS / NIR radiances is by comparison to calculated radiances over well-characterized ground sites under clear-sky conditions. The forward model used for the calculations is based on the SBDART software package (Ricchiazzi *et al.* 1999). The best ground sites are MODIS validation field sites, such as Railroad Valley Playa in Nevada, and White Sands in New Mexico. These sites have bright surfaces, uniform on the 2 km scale of VIS / NIR pixels, and MODIS in-situ teams provide information on the aerosol content of the atmosphere, the temperature and water vapor profiles, and the surface reflectance at Visible/Near-IR wavelengths. ARM CART sites are also useful because of the wide range of instruments available, though their non-uniform surface degrades the accuracy of the forward calculation. The MODIS Calibration Group has provided sample data files from Railroad Valley for evaluation and test (Thome, personal communication).

Secondary radiance validation is by direct comparison to select MODIS and AVHRR channels over cloud-free regions believed to be relatively homogeneous, thereby minimizing errors due to imperfect co-registration. Proposed regions for this are the Railroad Valley in Nevada, White Sands New Mexico, the Amazon Rain Forest in Brazil, and the Sahara Desert in Africa. The spectral channels comparable among the instruments are:

VIS / NIR Channel 1 is similar to a linear combination of MODIS channels 8 and 9, as described in the AIRS Level 1b ATBD, Part 2, Section 2.4.

VIS / NIR Channel 2 is similar to AVHRR Channel 1. It can also be compared to a linear combination of MODIS channels 1, 14, and 19, as described in the AIRS Level 1b ATBD, Part 2, Section 2.4.

VIS / NIR Channel 3 is similar to AVHRR Channel 2. It can also be compared to a linear combination of MODIS channels 2, 15, and 19, as described in the AIRS Level 1b ATBD, Part 2, Section 2.4.

VIS / NIR Channel 4 is similar to a linear combination of MODIS channels 1, 3, 4, 8 15, and 19, as described in the AIRS Level 1b ATBD, Part 2, Section 2.4.

Because MODIS and AIRS are imaging the same regions simultaneously, radiance validation against MODIS is most straightforward. This validation cannot occur, however, until MODIS has completed their initial check-out and calibration. AVHRR data is not collected simultaneously with AIRS, requiring a statistical comparison of radiances, but has the advantage of being available immediately.

The noise and stability of Level 1b VIS / NIR radiances will also be validated and monitored. Every VIS / NIR detector takes 8 dark current readings per scan line, and long-term monitoring of the average and standard deviation of these observations provides a measure of the noise level and stability of the detectors—and can be compared to values measured pre-launch. Secondary targets for noise and stability monitoring are ground targets believed to be well characterized or stable, and the on-board calibration lamps. Both these secondary targets, however, are possibly variable, making it difficult to interpret any variations that might be seen.

Software Tools Needed

To compare model calculations to data over select ground sites, the VIS / NIR forward model must be modified to accept the MODIS field data as input. Software is then needed to make scatterplots of the forward model against real data. To compare radiances among the instruments, software is needed that makes scatterplots of co-located observations, and generates the linear combinations of MODIS data along with any needed corrections to the AVHRR data. In addition, the software must be capable of binning and averaging data by location and local time.

Software needed for noise and stability monitoring are plots of single VIS / NIR detectors as a function of time, for select calibration or scene footprints, and the ability to calculate statistical moments for each detector on these select footprints. Subsetting of AIRS data based on the VIS Detector Temperature and Scan Head Housing Temperature (engineering parameters) is desirable.

2) Cloud and Low-Cloud Detection

VIS / NIR has two cloud flags. One flags whether or not a cloud is in the field of view of a pixel, while the second flags whether or not a detected cloud is "low" (within ~2 km of the surface). Primary validation of both flags is against cloud data from the Great Plains ARM CART site and observations made at UCSB. Lidar data from ARM CART or any other location (including aircraft underflights) is considered the best comparison to make. In addition, a graduate student at UCSB will operate a flux radiometer and visually classify any clouds seen from the ground during select AIRS overpasses. This information will be most useful for validating the low-cloud detection algorithm, as such clouds are common above UCSB at certain times of the year.

Another validation source for the AIRS cloud flags is via comparison to the MODIS cloud-mask (when it becomes available) and a statistical comparison to AVHRR/CLAVR cloud products. (The lack of simultaneous observations between AIRS and AVHRR necessitates a statistical approach.) The consistency of AIRS IR products with the VIS / NIR cloud flags will also be monitored. Strong correlations should be seen between the IR and VIS / NIR cloud fractions, and between the VIS / NIR low-cloud flag and the IR cloud-top temperature.

The performance of the AIRS low-cloud flag will be assessed under various conditions: when low-clouds are present by themselves, when low-clouds are present in addition to higher-level clouds, when low clouds are absent but higher clouds are present, and for clear-sky cases. Statistics on the accuracy of the AIRS low-cloud flag under each of these conditions will be generated.

Software Tools Needed

Software needed to validate the cloud flag consists of routines to ingest ARM CART observations and UCSB reports and compare them to co-located AIRS data. The ability to ingest MODIS and AVHRR/CLAVR data is also needed, as is the ability to generate statistical comparisons of all data sets over regions or conditions selected by the user. Criteria for data selection are location and time, latitude, solar zenith angle, AIRS look angle, and surface type. Quantities to calculate are fractional time the two data sets agree that a cloud is present, fractional time they agree the sky is clear, fractional time they agree the cloud state is unknown, fractional time AIRS is clear and the other is cloudy (and *vice versa*), fractional time AIRS is unknown and the other is cloudy, and the fractional time AIRS is unknown and the other is clear. The software must also perform spatial averaging of the AIRS data for comparison to the 8 km CLAVR footprint, or average the MODIS data to the VIS / NIR pixel size.

3) Variability Indices

VIS / NIR generates two variability indices for each IR footprint, one for all pixels within the footprint, the other for only those pixels believed to be clear. The Indices are simple functions of the L1B radiances, so validation of the radiances and the cloud flag also validates the calculated indices. The usefulness of the indices, however, needs to be demonstrated and validated. This is achieved by comparing the calculated indices with the internal error estimates on AIRS retrieved quantities, and with the number of cloud layers detected by AIRS. The stronger the correlation between the indices and these AIRS products, the more useful the indices are as a diagnostic.

Software Tools Needed

Software is needed to view (scatterplot) and calculate correlation coefficients between various error measurements and the VIS / NIR indices, and between the number of retrieved cloud layers and the VIS / NIR indices. AIRS error estimates include the error bars assigned to temperature and moisture profiles, column moisture, surface temperature, and the radiance residuals between observed and retrieved IR spectra. The software must allow for selection of data based on latitude, look angle, surface type, and solar zenith angle.

16.5. VIS / NIR Validation Data Sets

Below are listed data sets organized by the priority of the product they validate. The table below presents a prioritized list of the validation data.

1) Radiance

In Situ Data Sets: Surface characterization of MODIS and ARM ground sites.

Ground-based Instrument Data Sets: See *in situ* data.

Aircraft Data Sets: None.

Satellite Data Sets: MODIS, AVHRR.

Computer Models: Radiative transfer forward model.

2) Cloud and Low-Cloud Flags

In Situ Data Sets: None.

Ground-based Instrument Data Sets: LIDAR, MFRSR, observer reports.

Aircraft Data Sets: LIDAR, Observer reports.

Satellite Data Sets: MODIS, AVHRR/CLAVR.

Computer Models: None.

3) Variability Indices

In Situ Data Sets: None.

Ground-based Instrument Data Sets: None.

Aircraft Data Sets: None.

Satellite Data Sets: AIRS internal error estimates and retrieved quantities.

Computer Models: None.

Primary Data Sets	**Validation Use**
Radiative Transfer Model	Radiance
Ground-site Characterization	Radiance
LIDAR (ground-based)	Cloud
LIDAR (a/c-based)	Cloud
MFRSR (ground-based flux radiometer)	Cloud
Ground Observer	Cloud
A/C Observer	Cloud
AIRS Level 2 Data with Error Estimates	Variability

Secondary Data Sets	**Validation Use**
MODIS	Radiance, Cloud
AVHRR/CLAVR	Radiance, Cloud

Table 31. Primary and secondary VIS / NIR validation data sets.

16.6. Additional VIS / NIR Cloud Validation Activities

See Methodologies section.

16.7. VIS / NIR Data Sources

Aircraft observer reports
Validation Use: Cloud and Low-Cloud Flags.
Source: Validation field campaigns.
Contact: TBD

AVHRR
Validation Use: Radiance, Cloud Flags.
Source: NOAA.
Contact: Satellite Active Archive at www.saa.noaa.gov.

CLAVR
Validation Use: Cloud Flags.
Source: NOAA/NESDIS.
Contact: Larry McMillin.

Ground observer reports

Validation Use: Cloud Flags.
Source: WMO, validation field campaigns.
Contact: TBD.

Ground-site characterization
Validation Use: Radiance.
Source: ARM Program, MODIS.
Contact: Kurt Thome, University of Arizona.

LIDAR (Ground-Based)
Validation Use: Cloud Flags.
Source: ARM Program.
Contact: TBD

LIDAR (Aircraft-Based)
Validation Use: Cloud Flags.
Source: Validation field campaigns.
Contact: TBD

MODIS
Validation Use: Radiance, Cloud Flags.
Source: EOS, MODIS.
Contact: EOSDIS, Kurt Thome.

Radiative Transfer Model
Validation Use: Radiance
Source: UCSB.
Contact: Catherine Gautier.

17. Validation of Microwave Precipitation Estimates

17.1. Introduction

AIRS / AMSU / HSB will measure global precipitation twice per day over at least one annual cycle. Although there are many other sources of precipitation information, the absolute accuracy of any single method as it applies to instantaneous averages over several kilometers or more is arguably no better than perhaps a factor of two. By averaging independent measurements over large cells in space and time, better agreement can be obtained. The gross characterization of rainfall measurement errors was discussed by Wilheit (1988) who showed that, even for very pessimistic assumptions, random precipitation measurement errors were inconsequential in monthly rainfall averages over 5-degree squares, although the residual may depend on the precipitation type. For shorter time periods in smaller areas, sampling errors become dominant. Some early studies of such errors (e.g. Shin and North, 1988) were based on the 1974 GATE experiment in the ITCZ in the Eastern Atlantic. Later Chang et al. (1993) studied random errors in SSM/I precipitation retrievals, and found that they were dominated by sampling errors even in monthly 5-degree averages. Retrievals partitioned into even and odd days agreed with GATE-based estimates for the rainiest boxes, but the percentage error increased roughly as the inverse square root of the total rain. This suggests that a principal limitation to rainfall statistical accuracy is the frequency of observation, particularly when observations are restricted to the nominal 12-hour intervals of AIRS/AMSU/HSB. For this reason it is most important to validate AIRS/AMSU/HSB precipitation retrievals with respect to statistical averages, preferably partitioned by precipitation type or climate category.

The accuracy of alternative validation data sources at specific points in time and space are discussed below.

17.2. Precipitation Validation Requirements

The microwave precipitation have no validation requirements.

17.3. Precipitation Validation Requirements and Priorities

The precipitation validation program has three objectives. First, it is important to validate the accuracy of statistical averages computed over specific geographic cells and time periods, where 5-degree squares and one-month time averages constitute one widely used representation. A second form of validation involves point accuracies which are relevant to diagnostics of particular storm systems for which multiple observations and numerical models may be combined and compared. A third form of validation involves the validity of precipitation flags, or absence thereof, applied to explain or predict anomalies in AMSU/HSB radiances. For example, it would be useful to know whether a cold anomaly in AMSU/HSB tropospheric brightness temperatures was due to precipitation or to a cold non-precipitating air mass.

17.4. Precipitation Validation Methods and Data

Perhaps the best precipitation validation data set currently available over the continental United States is the WSI Inc. national mosaic processed NEXRAD radar product (http://www.wsicorp.com/wsicorp/product/dataprod/radar.htm). These radar-derived precipitation estimates, after being smoothed to match the 50-km resolution of AMSU, agreed with AMSU retrievals over 4 mm/h with only 1.4-dB rms discrepancies on four days during which the Eastern United States was experiencing either a hurricane or a strong frontal passage (Staelin and Chen, 2000). The NEXRAD and AMSU data were typically coincident within several minutes. AIRS/AMSU/HSB precipitation products can also be coarse-grained to match on pentad and monthly scales the 2.5-degree grid which is produced by the Global Precipitation Climatology project based on SSM/I, GOES, and rain gauges; comparison will reveal any spatial and seasonal biases.

Additional assets available for comparison include TRMM radar, WSR-88D and other radars around the world, TOVS, and others. In addition, the unlikely possible identification by AMSU/HSB of clear air phenomena as precipitating would be detectable by the coincident AIRS data.

17.5. Additional Precipitation Validation

Many meteorological systems overflown by AIRS/AMSU/HSB will be of research interest and will likely result in scientific studies conducted by one or more groups. The incorporation of AIRS/AMSU/HSB precipitation retrievals into these studies would be mutually beneficial, and would provide an additional source of validation information. In addition, numerical weather prediction models are increasingly capable of estimating stratiform precipitation, thus providing an additional source of validation information in locations where other sources are less reliable. The advantages of such comparison and validation are mutual.

17.6. Precipitation Validation Data Sources

NEXRAD, TRMM WSR-88D radar, TOVS, AIRS (clear air precipitation only); numerical weather prediction models.

18. References

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